Year: 2012

Soil organic carbon and nitrogen accumulation rates in cold and alpine environments over 1Ma

Egli, Markus ; Favilli, Filippo ; Krebs, Rolf ; Pichler, Barbara ; Dahms, Dennis

Abstract: Using published and new chronosequence datasets from the European Alps and the Wind River Range (Rocky Mountains, USA), we report for the first time a chronosequence of more than 1 Ma for soil organic carbon, nitrogen and organic matter (SOM) fractions from alpine soils. The investigated parameters include total carbon and nitrogen as well as the stable (resistant to H O oxidation) C and N fractions. Time trends were analysed and are reported on the basis of stocks and concentrations. The accumulation rates of C and N strongly decreased with increasing soil age. Differences in trends between the European Alps and the Wind River Range might be attributed to the factor climate. For the drier Wind River Range, an asymptotic value of about 15 kg C m ^{2} was reached after about 15 ky while an asymptotic value of 20–25 kg C m ^{2} was measured for the moister European Alps after about 3 ky. The difference in N stocks between the two regions was less obvious. For both areas, N was in the range of 0.5–2kgN m ^{2}. Using the exponential decay model, a steady state of C and N (stable and total) concentrations in the topsoil seemed to be reached after b1 ky (Alps) and 10 ky (Wind River Range). The retardation effect observed for the Wind River Range could probably be due to aeolian influx. For both areas, the asymptotic value of the stable fraction of C and N was in the range of 1–3 kg C m ^{2} and 0.2–0.4 kg N m ^{2}, respectively. The stable organic fraction often has an age close to the age of the soils and consequently can reach thousands of years. The relative proportion of N and amides was higher in the stable organic fraction compared to the bulk soil. The sequestration rates of org. C and N in soils of the European Alps and the Wind River Range can reach very high values in very young soils whereas in old soils sequestration rates are several orders of magnitude lower. Old soils often integrate several cold and warm phases and different vegetation types. Nonetheless, the factor Time seems to be very dominant and covers the track of other factors in old soils.

DOI: https://doi.org/10.1016/j.geoderma.2012.03.017

Originally published at:
Egli, Markus; Favilli, Filippo; Krebs, Rolf; Pichler, Barbara; Dahms, Dennis (2012). Soil organic carbon and nitrogen accumulation rates in cold and alpine environments over 1Ma. Geoderma, 183-184:109-123.
DOI: https://doi.org/10.1016/j.geoderma.2012.03.017

Soil organic carbon and nitrogen accumulation rates in cold and alpine environments over 1Ma

Markus Egli[1]*, Filippo Favilli[3], Rolf Krebs[4], Barbara Pichler[1], Dennis Dahms[2]

[1]Department of Geography, University of Zurich, CH-8057 Zurich, Switzerland

[2]Department of Geography, University of Northern Iowa, Cedar Falls, USA

[3]Institute of Biometeorology, CNR, Florence and FoxLab, E. Mach Foundation, Via E. Mach 1, 38010 San Michele a/Adige (Trento), Italy

[4]Institute of Natural Resource Sciences, Zurich University of Applied Sciences, Wädenswil, Switzerland

*E-mail of the corresponding author: markus.egli@geo.uzh.ch

Abstract

Using published and new chronosequence datasets from the European Alps and the Wind River Range (Rocky Mountains, USA), we report for the first time a chronosequence of more than 1 Ma for soil organic carbon, nitrogen and organic matter (SOM) fractions from alpine soils. The investigated parameters include total carbon and nitrogen as well as the stable (resistant to H_2O_2 oxidation) C and N fractions. Time trends were analysed and are reported on the basis of stocks and concentrations. The accumulation rates of C and N strongly decreased with increasing soil age. Differences in trends between the European Alps and the Wind River Range might be attributed to the factor climate. For the drier Wind River Range, an asymptotic value of about 15 kg C m^{-2} was reached after about 15 ky while an asymptotic value of 20-25 kg C m^{-2} was measured for the moister European Alps after about 3 ky. The difference in N stocks between the two regions was less obvious. For both areas, N was in the range of 0.5-2 kg N m^{-2}. Using the exponential decay model, a steady state of C and N (stable and total) concentrations in the topsoil seemed to be reached after <1ky (Alps) and 10 ky (Wind River Range). The retardation effect observed for the Wind River Range could probably be due to aeolian influx. For both areas, the asymptotic value of the stable fraction of C and N was in the range of 1-3 kg C m^{-2} and 0.2-0.4 kg N m^{-2}, respectively. The stable organic fraction often has an age close to the age of the soils and consequently can reach thousands of years. The relative proportion of N and amides was higher in the stable organic fraction compared to the bulk soil.

The sequestration rates of org. C and N in soils of the European Alps and the Wind River Range can reach very high values in very young soils whereas in old soils sequestration rates are several orders of magnitude lower. Old soils often integrate several cold and warm phases and different vegetation types. Nonetheless, the factor *Time* seems to be very dominant and covers the track of other factors in old soils.

Keywords: Chronosequence, organic C, nitrogen, sequestration, accumulation, stable carbon

1. Introduction

The rates of reactions and their dependencies on environmental factors (e.g., climate) are of fundamental interest for the understanding of the soil system and its interaction with surrounding environmental conditions. In this context, the influence of climate and time on soil and landscape is of growing interest because of observed and predicted global climate changes.

Soils are traditionally understood as a function of the state-factors Parent material, Climate, Topography, Biological activity and Time (Jenny, 1941). Consequently, by choosing sampling sites minimising the effect of soil forming factors other than time, the influence of time on soil formation can be studied (chronosequence).

Soil organic matter is a unique soil property in the sense that it reaches an approximate steady state in <5000 to 20000 y, which is rapid when compared with the development of other soil properties (Birkeland, 1999). Accumulation rates of carbon and nitrogen appear to depend greatly on the age of the surface (or soil, respectively). In a review of Holocene chronosequence studies in a variety of ecosystems, Schlesinger (1990) found a much higher and more variable rate of C accumulation in soils <3 ka in age (5.7 g C m^{-2} y^{-1}) compared with soils ranging from 3 to 10 ka (2.4 g C m^{-2} y^{-1}). In Alpine environments, soils developed on silicate parent material can accumulate ~40 kg organic C m^{-2}, with frequent values between 15-25 kg C m^{-2} (Egli et al., 2008a). In the Swiss Alps, Egli et al. (2001) measured accumulation rates of 6.7-9 g C m^{-2} y^{-1} in a 400 y soil sequence and 2-4 g C m^{-2} y^{-1} for Podzols as old as 11000 y. Mavris et al. (2010) found C accumulation rates of 7-36 g C m^{-2} y^{-1}in a 150 y proglacial sequence. Lichter (1998) reported accumulation rates of 9g C m^{-2} y^{-1} for a chronosequence developed on coastal dunes in Michigan (USA) and McPeek et al. (2007) reported rates of 1-3 g C m^{-2} y^{-1} of 220-1070 y old soils developed on basalts in southern Iceland. He and Tang (2008) determined an annual organic carbon accumulation rate of 28 g m^{-2} y^{-1} in a proglacial area with soil ages of 180 years (max), while an accumulation rate of 3.5 g m^{-2} y^{-1} was measured for nitrogen. Similar rates were found on young debris flows (with 26.5 g C m^{-2} y^{-1}; Turk and Graham, 2009). Thus, when considering the development of soil organic matter pools, it is important to include studies focusing on the early stages of soil development, apparently because this is when the most rapid accumulation occurs.

As seen above, earlier studies of C and N accumulation rates generally have used chronosequences that cover only a few hundred to thousands of years (mostly the Holocene) and include only sequestration rates of carbon. In the present study we used a combination of new and previously published data from chronosequence studies to extend our understanding of C and N accumulation rates beyond Holocene-aged soils. In almost all previous cases, time trends of only total carbon or nitrogen were measured and nothing has been reported regarding different soil organic matter (SOM) fractions. Many chemical- and physical methods exist to characterise soil organic matter. Soil organic carbon is known to contain a stable fraction with an old radiocarbon age and fractions that are more labile and have a lower turn-over rate (e.g. Eusterhues et al., 2003; Helfrich et al., 2007; Favilli et al., 2008). In this paper, consequently, different pools, such as the stable and labile fractions of carbon and nitrogen in the soil chronosequences were considered as well.

2. Study sites

New and previously published datasets on soil chronosequences were compared in order to differentiate several trends within larger regions or to complete trends with additional data (Tables 1 and 2; see also Dahms et al., 2011); in this case a chronosequence from the Wind River Range (Wyoming) sites was compared with chronosequences from the European Alps. All Alpine soils developed in formerly glaciated areas. Parent material was mostly (granitic/paragneiss) glacial till (different types of moraines) and in some cases in the Alps, relict rockglaciers. The soils of the Wind River Range have developed on granitic till (end and lateral moraines). The Wind River Range soils also are influenced by varying amounts of aeolian influx (Dahms, 1993; Dahms and Rawlins, 1996). The aeolian input is estimated to be in the range of 0.23 to 31.0 x 10^{-7}g cm^{-2} d^{-1} for parts of the western slope of the range (Dahms and Rawlins, 1996).

The mean annual precipitation and temperature of the individual investigation sites are given in Tables 1 and 2. In general, the European sites have a moister climate (1100-2000 mm/y) than the Wind River Range (around 400-1000 mm/y). Depending on the age of the surfaces, pioneer plant communities, shrubs or grassland and forest vegetation developed.

The moraines and consequently the soils usually could be clearly attributed to glacial stages such as deposits LGM (or soon thereafter; LGM = Lateglacial Maximum), Daun (Oldest Dryas), Egesen (Younger Dryas; 1 to 3 phases), Holocene-aged moraines, recent moraines. Relative and numeric age dating enabled the discrimination of additional landforms in the Rocky Mountains that could be attributed to older glacial events of the Pleistocene (Dahms, 2004). In the European Alps, soil chronosequences were available with ages up to about 20 ky and in the Wind River Range, with ages to about 1.2 Ma.

3. Materials and methods

3.1. Soil sampling

Soil material was sampled from excavated profile pits on undisturbed locations where no influence of creeping processes was visible. When possible, profiles were opened to expose C horizon material. 2-3 kg of soil material per horizon were taken for the analyses (Hitz et al., 2002). Bulk density was obtained for Alpine soils (fine earth and soil skeleton) using a soil core sampler with a specific volume or by excavated holes with a volume of about 500 – 2000 ml that were backfilled with a measureable volume of quartz sand (see e.g. Egli et al., 2003; Mavris et al., 2010 etc.). For the Rocky Mountain soils, bulk density was obtained using the paraffin-clod method for gravel-free peds using a gravel density of 2.6 g cm^{-3} (Singer and Janitzky, 1986). Oven-dried (70°C) samples were sieved to < 2 mm. This enabled the separation into fine earth and rock/skeleton fragments.

3.2. Total content and fractionation of organic matter

Total organic C and N contents both of the sola (fine earth) and parent material of the soils were measured with a C/H/N analyzer (Elementar Vario EL). To characterise the SOM in more detail, a fractionation procedure was applied using an oxidation treatment (H_2O_2). This approach is based on the oxidation of OM by 10% H_2O_2 (Eusterhues et al., 2005; Plante et al., 2004, modified). 1 gram of air-dried, untreated soil (< 2mm) was wetted for 10 min with distilled water in a 150 ml beaker. Following this, 90 ml of 10% H_2O_2 were added, stirring constantly. The procedure was run at 50 °C throughout the treatment period in a closed system to avoid evaporation of the reagent. Peroxide treatment was performed for 168h (7 days); the samples then were washed three times with 40 ml deionised water, freeze-dried, and their weights recorded. The pretreated samples were then analysed for total C and N and radiocarbon dated, while organic matter functional groups were detected using DRIFT (Diffuse Reflectance Infrared Fourier Transform). The amount of organic C after the H_2O_2 treatment was related to the initial organic C content using a mass-balance approach to obtain the corresponding recoveries with

$$\text{Recovery} = (gC_{after} / gC_{before}) \times 100 \qquad (1)$$

Recovery values were calculated also for nitrogen.

The stable organic C and N fractions were measured for all sites of the Wind River Range and for selected sites of the European Alps (Val di Rabbi, Morteratsch, some sites of Gletsch and Schmadri).

3.3. DRIFT measurements

The samples used for DRIFT (Diffuse Reflectance Infrared Fourier Transform Spectroscopy) analyses were homogenised in a mill using a fine ball-mill (Zr) for 45 s (frequency 25.0), then dried at 70°C for 2 hours. Relative peak intensities were used for DRIFT analysis (Bruker, Tensor 27). Spectra were recorded from 4000 to 250 cm^{-1}.

In order to quantify the relative changes in the FT-IR spectra, we divided the values of the relative intensity (area) of each peak by the sum of the relative intensity of all the considered peaks and multiplied it by 100 using the software OPUS 6. An individual peak search and calculation of relative intensities (area) was done for the following peak ranges: (base1/base2)(cm^{-1}): 3000/2820, 1725/1710, 1660/1630, 1620/1600, 1535/1500, 1495/1470, 1470/1430, 1413/1333, 1190/1127, 1116/1050 and 1080/1030. An integration method was employed to calculate the relative concentration (OPUS 6) that used a linear background between the found bases (individual samples) and absorbance values. Major IR absorption bands and functional groups assignments are given in Table 3. Aliphatic compounds were calculated using the IR range 1480-1430 cm^{-1}. DRIFT measurements were performed both on the H_2O_2 treated and untreated soil material.

3.4. Radiocarbon dating of organic matter fractions

The CO_2 of the combusted samples was catalytically reduced over cobalt powder at 550°C to elemental carbon (graphite). After reduction, the mixture was pressed into a target and carbon ratios were measured by Accelerator Mass Spectrometry (AMS) using the tandem accelerator of the Institute of Particle Physics at the Swiss Federal Institute of Technology Zurich (ETHZ). The calendar ages were obtained using the OxCal 4.0.5 calibration program (Bronk Ramsey, 2001; 2009) based on the IntCal 09 calibration curve (Reimer et al., 2009). Calibrated ages are given in the 1 and 2 σ range (minimum and maximum value for each).

3.5. Carbon and nitrogen stocks

The total soil organic carbon, total nitrogen, stable carbon and stable nitrogen stocks were calculated according to the following equation:

$$S_{stock} = \sum_{i}^{dz} C_i d_i \rho_i (1 - RM) \qquad (2)$$

where S_{stock} denotes the abundance (kg/m^2) of the corresponding element and fraction, C the concentration of the element in the corresponding fraction (kg/t), d_i the thickness of layer i (m), ρ = soil density (t/m^3) and RM the mass proportion of rock fragments/soil skeleton.

In addition to our data, datasets about total organic C of the Rocky Mountains, the New Zealand Alps (presented in Bockheim et al., 2000) and Spitsbergen (Kabala and Zapart, 2011) were added.

3.6. Surface age dating

Age control of the sites was obtained from geomorphologic mapping (Maisch, 1981, 1992; Dahms, 2002, 2004), historical data and documents, surface exposure dating (^{10}Be, ^{26}Al; Tables 1 and 2; see also Dahms et al., 2011) and radiocarbon analyses.

Young surfaces (having an age of < 700 years) in glacier forefields were dated using glacier length measurements (with an annual resolution; see e.g. Mavris et al., 2010) or historical documents (see e.g., Zumbühl and Holzhauser, 1988; Egli et al., 2001). Older surfaces were dated based on the age obtained form organic remains (e.g., peat bogs, buried soils) or stable soil organic matter fractions (in soils) using radiocarbon (e.g. Maisch, 1981; Wipf, 2001; Favilli et al., 2009). Several glacial events (moraines) and consequently soils were dated through the analysis of cosmogenic nuclides from moraine boulders (e.g. Dahms, 2004; Fabel et al., 2004; Favilli et al. 2009; Böhlert et al. 2010). Geomorphic mapping of moraines ensured the correct attribution to stratigraphic units (Dahms 2002, 2004; Maisch, 1981, Wipf, 2001; Böhlert et al., 2010 etc.).

4. Results

4.1. Stocks and accumulation rates of organic C and N as a function of soil age

In the Alps, a sharp increase in the organic carbon abundance was measured in soils up to an age of approximately 3ky. For older soils, a roughly asymptotic value is reached at about 20 to 25 kg C m^{-2} (Fig. 1). Compared to the Alps, the rate of increase in org. C stocks is slightly lower in the Wind River Range (an asymptotic value is reached after about 15ky). This may be due to the effect of the drier climate conditions here. In any case, organic carbon values reach an asymptotic end value of about 10-15 kg C m^{-2}. With respect to nitrogen, however, no real differences were detectable in the trend between the Alps and the Wind River Range (Fig. 2). The asymptotic value for N is near 1 kg m^{-2}.

When we divide the stocks of C or N by the soil age we get the age specific accumulation rate (Figs. 1 and 2). The C sequestration rates were very high at the start of soil formation and could reach values of up to 100 g C m^{-2} y^{-1} (Fig. 1). In general, these accumulation rates are higher in the Alps than in the Wind River Range. The accumulation rates decreased distinctly with increasing soil age. Accumulation rates generally reached values of 0.8-3 g C m^{-2} y^{-1} for soils 10 ky-old while soils older than 100 ky had accumulation rates of 0.1 g C m^{-2} y^{-1} and less. Depending on the soil age, the N sequestration rates varied from about 10 g N m^{-2} y^{-1} down to 0.001 g N m^{-2} y^{-1}(Fig. 2).

4.2. Labile and stable organic matter

The concentrations of total, labile and stable organic C and N for the Wind River Range (WRR) are given in Table 4 and those of the European Alps in Table 5. Stable C and N usually are only a minor part of the total C and N.

Carbon recovery after oxidation by H_2O_2 was near 9% for the WRR samples and 7% for the Alps (median values; Fig. 3) whereas the recovery for nitrogen was much higher, at 23% (WRR) and 15% (Alps). Similar to previous investigations in the Alps (Favilli et al., 2008; Egli et al., 2010a), the C/N ratio of SOM dropped abruptly after the H_2O_2 treatment. The median C/N-value of the untreated soils was near 11 (WRR) and 20 (Alps), but was only ~5 (WRR) and 8 (Alps) after the H_2O_2 treatment. Compared to the untreated soils, the H_2O_2 treatment revealed a relative enrichment of nitrogen (lower C/N ratios after the treatment). The median C/N ratio of the labile SOM fraction was consequently higher (median value near 14 (WRR) and 22 (Alps)). This fraction is, thus, relatively enriched in carbon. It seems that SOM in the Alps contains more labile OM that increases the C/N ratio of these soils.

The DRIFT spectra of the H_2O_2-treated samples showed that the oxidation-resistant OM was relatively enriched in proteic amides (Fig. 3), which illustrates the high nitrogen content of the resilient organic matter. The relative proportion of aliphatic C-H stretching (data not shown) was also increased after the treatment: a trend that has been observed in previous studies (Barbera et al., 2008; Favilli et al., 2008).

In Figure 4, the concentrations of C and N (total content and stable fraction) in the topsoil are plotted as a function of time (only paired samples where both types of measurements were available). In the Alps, these concentrations of C and N (total and stable fraction) increase very sharply during early soil formation. There is, however, a relatively strong scatter of the C concentrations that is not only due to the factor *Time* (but also to others such as for example vegetation).

With respect to the stable fractions stocks, an asymptotic value seems to be reached at about 1-3 kg C m^{-2} and 0.2-0.4 kg N m^{-2} (Fig. 5). The trends of stable C and N are quite similar for both areas, where quasi-steady state situation is reached after about 5-10 ky.

4.3. Age of the stable organic C

The age of the stable organic matter was determined in three soil profiles from the Wind River Range mapped as Holocene or Lateglacial (Wisconsin/Pinedale) age. Very high ages - up to more than 10 ky - were obtained from these samples (Table 6). The age of the resilient organic matter fraction generally increased with increasing soil depth. Several authors have described an increasing age trend with soil depth for the stable organic matter fractions (e.g. Scharpenseel and Becker-Heidmann, 1992; Rumpel et al., 2002). In Alpine soils, however, a reverse age-trend was reported down-profile for the stable organic matter fraction (using the H_2O_2 technique) along the profile was found in Alpine soils (Favilli et al., 2008, 2009). A soil that has experienced an undisturbed evolution should show a decreasing age of the stable organic matter with increasing soil depth - if one takes into account that soil organic matter derives mainly from organic litter which is produced first in the topsoil and not in the subsoil. Consequently, our age trends in some of the Wind River Range sites show that the soils do not have a fully undisturbed development history. This result is supported by Dahms (1993, 2002, 2004) and Dahms and Rawlins

(1996) who demonstrated that these soils appear to received a not insignificant aeolian influx. Theoretically, a continuous influx of Aeolian material should lead to an age inversion of the ages of the stable organic matter within the profile, which our present results appear to confirm.

5. Discussion

The high carbon and nitrogen sequestration rates that we report for the early stages of soil formation in the Wind River Range and the Alps are notable (Figs. 1 and 2). We note that similarly high have been measured in other alpine environments as well as in Arctic and Antarctic soils. Carbon and nitrogen storage can reach very high levels already in young soils (max. a few hundred years old; 6.2 kg C m^{-2} and 0.9 kg N m^{-2} in the King George Islands; Beyer et al., 2002). It would appear that a main cause for high rites of sequestration in young soils is the interaction with vegetation. Conen et al. (2007) and Burga et al. (2010) showed that vegetation cover and speciation develop quickly in proglacial areas which helps to accelerate the sequestration rate of organic C.

Resilient organic matter (which resists to the H_2O_2 treatment) could already be detected in the youngest soils of the Alps. It is remarkable that at very early stages of soil formation, a SOM fraction was present that was hardly oxidisable and strongly resilient. The low C/N ratio of this fraction points to its stability (see Favilli et al., 2008; Egli et al., 2010a). At least for those soils that showed undisturbed development since the Lateglacial (Pleistocene) and Holocene, the stable organic matter can be used as surface age indicator as this fraction nicely traces soil formation (Böhlert et al., 2011; Favilli et al., 2009). A similar situation (but slightly disturbed due to aeolian inputs) could be observed in the Wind River Range.

The trends we obtained are, in general, similar for the Alps and the Rocky Mountains (Wind River Range), with some notable differences. Especially at the beginning of soil formation, the variability of organic C and N in the uppermost soil horizons was considerable in the European Alps. Aside from the large-scale factor of *Time*, small-scale factors (the 'dot' facors of Jenny) such as water content of the substrate, the micro-relief and micro-climate seem to be crucial for both the development of the vegetation and, consequently, also the early evolution of the soils (Burga et al., 2010). The moister conditions in the European Alps favour rapid vegetation growth and humification processes that, in turn, accelerate the formation of soil organic matter. In fact, the slightly lower accumulation rates and retarded process reactions that we measured for the Wind River Range illustrates this relationship and we assume that the drier climate of the WRR might be the cause. The asymptotic total C and N stocks in the Alps are in the range of 20-25 kg C m^{-2} and 0.5-2 kg N m^{-2}; for the WRR the C stocks are probably lower (15 kg C m^{-2}) while N remains generally the same as in the Alps. In general, the accumulation (sequestration) rates of org. C and N in very young soils of the European Alps and the Wind River Range can reach very high values. These rates are close to those measured in soils of volcanic regions (see Zehetner, 2010). In newly aggrading ecosystems on young (<200-y-old) volcanic deposits, mean soil organic C accumulation reached 30-60 g m^{-2} y^{-1}; however, rates drop below 10 g C m^{-2} y^{-1} after approximately 1000 years and continuously level off during the following millennia (Zehetner, 2010). This general trend holds true also for alpine soils, but the values are probably slightly lower with about 5-50 g C m^{-2} y^{-1} for young soils (< 200 y old; see also Dümig et al., 2011) and mostly <5-10 g C m^{-2} y^{-1} after about 1000 years. Besides climatic differences, the usually higher amount of weakly crystalline mineral forms and ITM (imogolite type material) are most probably the cause for the slightly higher sequestration rate at volcanic sites (Shoji et al., 1993; Basile-Doelsch et al., 2005; Egli et al., 2008b).

The chronofunctions of the stable and total OM concentrations in the topsoil were fitted to data using the exponential decay model (Fig. 6; function shown only for the stable C and N). The exponential decay model (cf. Lichter, 1998) is given by

$$f(t) = a + (b - a)e^{-kt} \tag{3}$$

where *a* represents an asymptote, *b* the initial quantity, and k the decay constant. We use the decay model because it more closely agrees with theoretical expectations, whereas the power law function has the disadvantage that concentrations can theoretically reach infinite values (and the increase of C and N can hardly occur to infinite values). Using the exponential decay model, a steady state of C and N (stable and total) contents seems to be reached after <1ky in the Alps and by about 10 ky in the WRR. Particularly in the Alps, the uppermost soil horizons are quickly saturated with organic C (total and stable). In the Wind River Range, an asymptotic value seems to be reached later than in the European Alps. However, data for very young soils are missing and consequently a conclusive statement cannot be done. The asymptotic value for stable organic C is near 5.5 g/kg for the Alps and near 2.2 g/kg for the WRR. Stable nitrogen reaches an asymptotic value of 0.70 g/kg in the Alps and 0.32 g/kg in the WRR. Stable C and N concentrations in the topsoil reached in general higher values at Alpine sites than in the Wind River Range where the asymptotic values also seemed to be attained rather later than in the Alps (Fig. 6). This retardation may indicate some disturbances in the soil formation (Dahms, 2002; 2004). The difference can probably also be explained by the factor climate. Furthermore, the concentrations of the stable organic matter were lower in the Wind River Range soils. We hypothesise that the moisture conditions in the Alps lead to a higher production of secondary minerals (mainly clays) that enhance the fixation of stable organic compounds onto their surfaces. Among others, Kleber et al. (2007) and Kögel-Knabner et al. (2008) have shown the importance of the secondary mineral fraction in OM protection. According to the model proposed by Kleber et al. (2007), the formation of particularly strong organo-mineral associations appears to be favoured in the so-called 'contact zone' by situations where proteinaceous materials unfold upon adsorption, and increase adhesive strength by adding hydrophobic interactions to electrostatic binding.

For the European Alpine sites, no datasets for total and labile C and N were available for soils older than 30 ky. Consequently, any prediction beyond that age, for these sites, remains speculative and should be verified with older Alpine sites (> 100 ky).

Soils progressively develop with time, of course. As a result, soil thickness generally also increases (see e.g. Humphreys and Wilkinson, 2007; Sauer, 2010). The increase is in most cases not linear, as soil production has to counter-balance chemical and physical weathering losses (e.g. Brantley et al., 2007; Sauer, 2010; see also Fig. 7). Also in this case, often a kind of asymptotic end-value is said to be reached (Heimsath et al., 1997; Yoo and Mudd, 2008; Sauer, 2010; Fig. 7). Consequently, an increase in soil organic C and N stocks with time is not only due to an increase in the concentration in the uppermost soil horizons but also due to C and N production in deeper soil horizons and/or to translocation processes (Fig. 7). As a soil column becomes more evolved and thicker, the total abundance of C and N increases.

An important requirement for developing chronosequences such as ours is that the influence of soil forming factors other than time should become negligible (Jenny, 1941). However, this requirement can often not strictly be fulfilled. Pedogenesis through the observed time frame has not been continuous and completely similar. Especially for the Wind River Range sites, climate variability over the past ~1 Ma will have been considerable. Because of the extreme age of some of the soils in the Wind River Range (>500 ka) some sites will have experienced several warm and cold phases. These soils consequently integrate the effect of such climatic variations. For example, soils developed on Bull Lake-age piedmont moraines of the WRR (~130 ka, OIS-6) show thinner, coarser A-horizons than those on adjacent soils developed in Pinedale-age moraines (LGM, OIS-2). This anomaly was created when foehn winds off the active Pinedale glaciers stripped finer particles out of the Bull Lake A horizons. This process also caused A-horizon processes to affect the upper B-horizons of these soils (Hall, 1999; Applegarth and Dahms, 2001). We assume similar processes also were active on older deposits/soils.

The profile C and N density of alpine soils (Alps, WRR) increases with time of exposures, but the long-term accumulation rate also depends on climate. Interval-specific C accumulation rates could be estimated for some sites of the Alps and the WRR and compared to other considered sites (Bockheim et al., 2000). In the Alps (for the sites Gletsch, Schmadri, Val di Rabbi and Val

Mulix), the C accumulation rates are between 2.5 and 9 g C m^{-2} y^{-1} for soils that developed in the Holocene (very young soils < 1ky are excluded, because under these circumstances predominantly the factor *Time* accounts for the accumulation rate). Organic C accumulation rates in Alpine soils between c. 17 – 10 ky BP were in the range of 0.25 – 1.1 g C m^{-2} y^{-1}. The data from the Wind River Range soil show that during the last glaciation almost no org. C was sequestered in the soils while the C accumulation rate in the WRR after the glaciation was approximately 0.4 g C m^{-2} y^{-1} and during the Holocene (also excluding the very young soils) about 1.1 g C m^{-2} y^{-1}. The data fit very well with the calculations of Bockheim et al. (2000) that suggests rates of soil organic C accumulation increase during warmer periods. In cold-alpine regions, the growth of vegetation and the subsequent accumulation of org. C in the soil is temperature dependent. The effect of precipitation, however, also has to be considered: according to our results and those of Bockheim (2000), the soil C accumulation rates are higher in those alpine areas with more precipitation (cf. Alps vs. WRR). The approach of time-interval based calculations has, however, strong limitations. The factor *Time* seems to be very dominant and covers the track of other factors especially in old soils.

For our sites in the Wind River Range and the Alps, the soil forming factors except time are not completely constant or negligible; but as the soil pits were located at stable sites (topography) having a similar geochemical composition (parent material) and because the vegetation cannot be considered as a fully independent state factor, we hypothesise that the differences among sites are attributed predominantly due to the factors time and climate.

Despite such shortcomings, we find that similar distinct trends in soil formation with time exist between the Wind River Range and the European Alps, with smaller less distinct differences that are probably due to variations in climate factors.

6. Conclusions

We compared soil chronosequences from the European Alps and the Wind River Range (Rocky Mountains of Wyoming, USA) with respect to organic C content and sequestration rates as well as stable and labile forms of OC. From their comparison, a chronosequence of ~1Ma was made possible. Our general observations are that C and N sequestration rates are extremely high at the beginning of soil formation (up to 10-100 g m^{-2} y^{-1} for C and 0.5-5.5 g m^{-2} y^{-1} for N) and rapidly decline to low values with soil age. After about 20 ky, the C and N accumulation rates are below < 1 g C m^{-2} y^{-1} and 0.01 g N m^{-2} y^{-1}, respectively. The oldest soils have almost no net accumulation of organic C and N (rates are below 0.1 g C m^{-2} y^{-1} and 0.001 g N m^{-2} y^{-1}). The abundance of C in the soil seems to be lower in the Wind River Range (asymptotic value is near 10-15 kg C m^{-2}) than in the European Alps (asymptotic values is c. 20-25 kg m^{-2}). The differences for N are however small (for both areas, the asymptotic value is near 0.5 – 2 kg N m^{-2}). Furthermore, the concentrations of the stable C and N (H_2O_2 resistant fractions) in the topsoils are lower in the Wind River Range chronosequence, where also an asymptotic value seems to be reached. The trend is best explained by an exponential decay model. The achievement of the asymptotic value is apparently retarded in the Wind River Range soils because of sporadic aeolian inputs. The stable C and N stocks for both areas are in the range of 1-3 kg C m^{-2} and 0.2-0.4 kg N m^{-2}.
Interval-specific estimates of C accumulation rates showed that with warmer and moisture conditions more C was sequestered. We presume this pattern is the result of the integration of several cold/warm phases in the older (Pleistocene) soils.

7. Acknowledgements

We would like to thank B. Kägi and M. Hilf for the help in the laboratory. We are, furthermore, indebted to M. Vepraskas and to two unknown reviewers for their helpful comments on an earlier version of the manuscript.

References

Applegarth, M.T., Dahms, D.E., 2001. Soil catenas of calcareous tills, Whiskey Basin, Wyoming, USA. Catena 42, 17-38.

Barbera, V., Raimondi, S., Egli, M., Plötze, M. 2008. The influence of weathering processes on labile and stable organic matter in Mediterranean volcanic soils. Geoderma 143, 191-205.

Basile-Doelsch, I., Amundson, R., Stone, W.E.E., Masiello, C.A., Bottero, J.Y., Colin, F., Masin, F., Borschneck, D., Meunier, J.D., 2005. Mineralogical control of organic carbon dynamics in a volcanic ash soil on La Réunion. European Journal of Soil Science 56, 689-703.

Beyer, L., White, D.M., Blume, H.-P., Bölter, M., Kuhn, D., Pingpank, K., Vogt, B., 2002. Refractory soil organic matter – formation, accumulation, translocation and transformation. In: Beyer, L., Bölter, M. (Eds.), Geoecology of Antarctic ice-free coastal landscapes. Ecological Studies 154, Springer Verlag, Berlin, pp. 139-159.

Birkeland, P.W., 1984. Holocene soil chronofunctions, southern Alps, New Zealand. Geoderma 34, 115-134.

Birkeland, P.W., 1999. Soils and geomorphology. 3rd edition, Oxford University Press, New York, 430 pp.

Birkeland, P.W., Burke, R.M., Shroba, R.R., 1987. Holocene alpine soils in gneissic cirque deposits, Colorado Front Range. U.S. Geological Survey Bulletin 1590-E, E1-21, Washington.

Birkeland, P.W., Burke, R.M., Benedict, J.B., 1989. Pedogenic gradients for iron and aluminum accumulation and phosphorous depletion in arctic and alpine soils as a function of time and climate. Quaternary Research 32, 193-204.

Bockheim, J.G., Birkeland, P.W., Bland, W.L., 2000. Carbon storage and accumulation rates in alpine soils: evidence from Holocene chronosequences. In: Lal, R., Kjmble, J.M., Stewart, B-A. (eds), Global climate change and cold regions ecosystems. Advances in Soil Science, Lewis Publishers, Boca Raton, pp. 185-196.

Böhlert, R., Egli, M., Maisch, M. Brandová, D., Ivy-Ochs, S., Kubik, P.W., Haeberli, W. 2011. Application of a combination of dating techniques to reconstruct the Lateglacial and early

Holocene landscape history of the Albula region (eastern Switzerland). Geomorphology 127, 1-13.

Brantley, S.L., Goldhaber, M.B., Ragnarsdottir, K.V., 2007. Crossing disciplines and scales to understand the critical zone. Elements 3, 307-314.

Bronk Ramsey, C., 2001. Development of the radiocarbon calibration program OxCal. Radiocarbon 43, 355-363

Bronk Ramsey, C., 2009. Bayesian analysis of radiocarbon dates. Radiocarbon 51, 337-360.

Burga, C.A., Krüsi, B., Egli, M., Wernli, M., Elsener, S., Ziefle, M. & Mavris, C., 2010. Plant succession and soil development on the foreland of the Morteratsch glacier (Pontresina, Switzerland): Straight forward or chaotic? Flora, 205, 561-576.

Conen, F., Yakutin, M.V., Zumbrunn, T., Leifeld, J. 2007. Organic carbon and microbial biomass in two soil development chronosequences following glacial retreat. European Journal of Soil Science, 58, 758-762.

Dahms, D.E., 1993. Mineralogical evidence for eolian sediments in soils on Late Quaternary moraines, Wind River Mountains, Wyoming. Geoderma 59,175-196.

Dahms, D.E., Rawlins, C.L., 1996. A two-year record of eolian sedimentation in the Wind River Range, Wyoming, U.A.A. Arctic and Alpine Research 28, 210-216.

Dahms, D.E., 2002. Glacial Stratigraphy of Stough Creek Basin, Wind River Range, Wyoming. Geomorphology 42, 59-83.

Dahms, D.E., 2004. Relative and numeric age data for pleistocene glacial deposits and diamictons in and near Sinks Canyon, Wind River Range, Wyoming, U.S.A. Arctic, Antarctic, and Alpine Research 36, 59-77.

Dahms, D. Favilli, F., Krebs, R. Egli, M., 2011. Soil weathering and accumulation rates of poorly crystalline phases derived from a 1Ma chronosequence. Submitted.

Dümig. A., Smittenberg, R., Kögel-Knabner, I., 2011. Concurrent evolution of organic and mineral components during initial soil development after retreat of the Damma glacier, Switzerland. Geoderma 163, 83-94

Egli, M., Fitze, P., Mirabella, A,. 2001. Weathering and evolution of soils formed on granitic, glacial deposits: results from chronosequences of Swiss alpine environments. Catena 45, 19-47.

Egli, M., Zanelli, R., Kahr, G., Mirabella, A., Fitze, P. 2002. Soil evolution and development of the clay mineral assemblage of a Podzol and Cambisol in “Meggerwald” (Switzerland). Clay Minerals, 37, 351-366.

Egli, M., Mirabella, A., Fitze, P., 2003. Formation rates of smectites derived from two Holocene chronosequences in the Swiss Alps. Geoderma 117, 81-98.

Egli, M., Merkli, C., Sartori, G., Mirabella, A., Plötze, M. 2008a. Weathering, mineralogical evolution and soil organic matter along a Holocene soil toposequence on carbonate-rich materials. Geomorphology, 97, 675-696.

Egli, M., Mirabella, A., Nater, M., Alioth, L., Raimondi, S. 2008b. Clay minerals, oxyhydroxide formation, element leaching and humus development in volcanic soils. Geoderma, 143, 101-114.

Egli, M., Mavris, C., Mirabella, A., Giaccai, D., Kägi, B., Haeberli, W., 2010a. Soil organic matter formation along a chronosequence in the Morteratsch proglacial area (Upper Engadine, Switzerland). Catena 82, 61-69.

Egli, M., Brandová, D., Böhlert, R. Favilli, F., Kubik, P., 2010b. ^{10}Be inventories in Alpine soils and their potential for dating land surfaces. Geomorphology 119, 62-73

Eusterhues, K., Rumpel, C., Kleber, M., Kögel-Knabner, I., 2003. Stabilization of soil organic matter by interactions with minerals as revealed by mineral dissolution and oxidative degradation. Organic Geochemistry 34, 1591-1600.

Eusterhues, K., Rumpel, C., Kögel-Knabner, I., 2005. Stabilization of soil organic matter isolated via oxidative degradation. Organic Geochemistry 36, 1567-1575.

Fabel, D., Harbor, J., Dahms, D., James, A., Elmore, D., Horn, L., Daley, K., Steele, C., 2004. Spatial patterns of glacial erosion at a valley scale derived from terrestrial cosmogenic ^{10}Be and ^{26}Al concentrations in rock. Annals of the Association of American Geographers 94, 241-255.

Favilli, F., Egli, M., Cherubini, P., Sartori, G., Haeberli, W., Delbos, E., 2008. Comparison of different methods of obtaining a resilient organic matter fraction in Alpine soils. Geoderma 145, 355-369.

Favilli, F., Egli, M., Brandová, D., Ivy-Ochs, S., Kubik, P.W., Cherubini, P., Mirabella, A., Sartori, G., Giaccai, D., Haeberli, W., 2009. Combined use of relative and absolute dating techniques for detecting signals of Alpine landscape evolution during the late Pleistocene and early Holocene. Geomorphology, 112, 48-66.

Guo, Y., Bustin, R.M., 1997. Micro-FTIR spectroscopy of liptinite macerals in coal. International Journal of Coal Geology 36, 259-275.

Hall, R.D., 1999. Effects of climate change on soils in glacial deposits, Wind River Basin, Wyoming. Quaternary Research 51, 248-261.

Hantke, R., 1983. Eiszeitalter 3: Die jüngste Erdgeschichte der Schweiz und ihrer Nachbargebiete. Westliche Ostalpen mit ihrem bayerischen Vorland bis zum Inn-Durchbruch und Südalpen zwischen Dolomiten und Mont-Blanc. Ott Verlag, Thun, Switzerland.

He, L., Tang, Y., 2008. Soil development along primary succession sequences on moraines of Hailuogou Glacier, Gongga Mountain, Sichuan, China. Catena 72, 259-269.

Heimsath, A.M., Dietrich, W.E., Nishiizumi, K., Finkel, R.C., 1997. The soil production function and landscape equilibrium. Nature 388, 358–361.

Helfrich, M., Flessa, H., Mikutta, R., Dreves, A., Ludwig, B., 2007. Comparison of chemical fractionations methods for isolating stable soil organic carbon pools. European Journal of Soil Science 58, 1316-1329.

Hitz, C., Egli, M., Fitze, P., 2002. Determination of the sampling volume for representative analysis of alpine soils. Zeitschrift für Pflanzenernährung und Bodenkunde 165, 326-331.

Humphreys, G.S., Wilkinson, M.T., 2007. The soil production function: A brief history and its rediscovery. Geoderma 139, 73-78.

Jenny, H. 1941., Factors of Soil Formation. McGraw-Hill, New York.

Kabala, C., Zapart, J., 2011. Initial soil development and carbon accumulation on moraines of a rapidly retreating Werenskiold Glacier, SW Spitsbergen, Svalbard archipelago. Geoderma, accepted.

Keller, O., Krayss, E., 1993. The Rhine-Linth Glacier in the upper Würm: A model of the last Alpine glaciation. Quaternary International 18, 15-27.

Kleber, M., Sollins, P., Sutton, R., 2007. A conceptual model of organo-mineral interactions in soils: self-assembly of organic molecular fragments into zonal structures on mineral surfaces. Biogeochemistry 85, 1, 9-24.

Kögel-Knabner, I., Guggenberger, G., Kleber, M., Kandeler, E., Kalbitz, K., Scheu, S., Eusterhues, K., Leinweber, P., 2008. Organo-mineral associations in temperate soils: Integrating biology, mineralogy, and organic matter chemistry. Journal of Plant Nutrition and Soil Science 171, 61-82.

Lichter, J., 1998. Rates of weathering and chemical depletion in soils across a chronosequence of Lake Michigan sand dunes. Geoderma, 85: 255-282.

Mahaney, W.C., 1974. Soil stratigraphy and genesis of Neoglacial deposits in the Arapaho and Henderson cirques, central Colorado Front Range. Quaternary Environments, Geographical Monogr. 5, 197, York University Press, Downsview, Ontario.

Mahaney, W.C., 1978. Late-Quaternary stratigraphy and soils in the Wind River Mountains. Western Wyoming. Quaternary Soils, Geographical Abstracts, Norwich, CT.

Maisch, M., 1981. Glazialmorphologische und gletschergeschichtliche Untersuchungen im Gebiet zwischen Landwasser- und Albulatal (Kt. Graubünden, Schweiz). Physische

Geographie 3. Furrer, G., Keller, W.A., Gamper, M., Suter, J. (Eds). Institute of Geography, University of Zurich.

Maisch, M., 1992. Die Gletscher Graubündens: Rekonstruktion und Auswertung der Gletscher und deren Veränderung sit dem Hochstand von 1850 im Gebiet der östlichen Schweizer Alpen (Bündnerland und angrenzende Regionen). Schriftenreihe Physische Geographie 32, Universität Zürich-Irchel, Switzerland.

Maisch, M., 2000. The longterm signal of climate change in the Swiss Alps: glacier retreat since the end of the little ice age and future decay scenarios. Geografia Fisica e Dinamica Quaternaria 23, 139-151.

Maisch, M., Brandova, D., Ivy-Ochs, S., Kubik, P.W., 2005. Exposure dating on moraines of the Morteratsch glacier (Bernina region, Upper Engadine, GR). In: Haeberli, W., Giardini, D. (eds.), Proceedings of the 3rd Swiss Geoscience Meeting, Zürich, pp. 181-182.

Mavris, C., Egli, M., Plötze, M., Blum, J., Mirabella, A., Giaccai, D., Haeberli, W., 2010. Initial stages of weathering and soil formation in the Morteratsch proglacial area (Upper Engadine, Switzerland). Geoderma, 155, 359-371.

McPeek, T., Wang, X.Z., Brown, K., Filipelli, G.M., 2007. Rates of carbon ingrowth and nutrient release from young Icelandic basalts. JOKULL 57, 37-44.

Piccolo, A., Mirabella, A., 1985. Effetto di differenti estraenti inorganici e organici su alcune proprietà chimiche e chimico-fisiche di un acido umico. Annali dell'Istituto Sperimentale per lo Studio e Difesa Suolo XVI, 159-168.

Plante, A.F., Chenu, C., Balabane, M., Mariotti, A., Righi, D., 2004. Peroxide oxidation of clay-associated organic matter in a cultivation chronosequence. European Journal of Soil Science 55, 471-478.

Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C., Buck, C.E., Burr, G.S., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Hajdas, I., Heaton, T.J., Hogg, A.G., Hughen, K.A., Kaiser, K.F., Kromer, B., McCormac, F.G., Manning, S.W., Reimer, R.W., Richards, D.A., Southon, J.R., Talamo, S., Turney, C.S.M., van der Plicht, J., Weyhenmeyer, C.E., 2009. INTCAL09 and MARINE09 radiocarbon age calibration curves, 0-50,000 years cal BP. Radiocarbon 51, 1111-1150.

Rumpel, C., Kögel-Knabner, I., Bruhn, F., 2002. Vertical distribution, age and chemical composition of organic carbon in two forest soils of different pedogenesis. Organic Geochemistry 3, 1131-1142.

Sauer, D., 2010. Approaches to quantify progressive soil development with time in a Mediterranean climate – I, Use fo field criteria. Journal of Plant Nutrition and Soil Science 173, 822-842.

Schlesinger, W.H. 1990. Evidence from chronosequence studies for a low carbon storage potential of soils. Nature 348, 232–234.

Scharpenseel, H.W., Becker-Heidmann, P., 1992. Twenty-five years of radiocarbon dating soils: Paradigm of erring and learning. Radiocarbon 34, 541-549.

Senesi, N., V. D'Orazio, G. Ricca, 2003. Humic acids in the first generation of EUROSOILS. Geoderma 116, 325-344.

Shoji, S., Nanzyo, M., Dahlgren, R.A., 1993. Volcanic Ash Soils – Genesis, Properties and Utilization. Elsevier, Amsterdam.

Singer, M. J., Janitzky, P., 1986. Field and laboratory procedures used in a soil chronosequence study. U.S. Geological Survey Bulletin, 1648.

Stevenson, F.J., 1994. Humus chemistry: genesis, composition, reactions. 2nd ed., Wiley, New York.

Tan, K. H., 2003. Humic Matter in Soil and the Environment. Marcel Dekker, Inc., New York.

Turk, J.K., Graham, R.C., 2009. Soil carbon and nitrogen accumulation in a forested debris flow chronosequence, California. Soil Science Society of America Journal 73, 1504-1509.

Wipf, A., 2001. Gletschergeschichtliche Untersuchungen im spät- und postglazialen Bereich des Hinteren Lauterbrunnentals (Berner Oberland, Schweiz). Geographica Helvetica 56, 133-144.

Yoo, K., Mudd, S.M., 2008. Toward process-based modelling of geochemical soil formation across diverse landforms: A new mathematical framework. Geoderma 146, 248-260.

Zehetner, F., 2010. Does organic carbon sequestration in volcanic soils offset volcanic CO2 emissions? Quaternary Science Reviews 29, 1313-1316.

Zumbühl, H.J., Holzhauser, H., 1988. Alpengletscher in der Kleinen Eiszeit. Die Alpen, Zeitschrift des Schweizerischen Alpen-Clubs, 129-322.

Table 1
Click here to download Table: Table1.doc

Table 1. Characterstics of the Wind River Range sites.

Site / soil profile	Longitude °E	Latitude °N	Elevation m asl	Aspect °N	Slope %	Parent material	Location	Vegetation	Soils (Soil Taxonomy; Soil Survey Staff, 2010)	Soil age y	MAP mm/y	MAT °C	Source
Bigfoot Lake													
9	109° 1'7"	42°38'12"	3414	-	0	Granitic till	end moraine	Lichen-covered boulders	Typic Cryorthent	150	800-900	-3.3	Dahms, 2002;
6	109° 1'4"	42°38'22"	3365	-	0	Granitic till	end moraine	Alpine grassland	Typic Haplocryoll	9930	800-900	-3.0	
5	109° 0'57"	42°38'22"	3353	-	0	Granitic till	lateral/end moraine	Alpine grassland	Typic Haplocryoll	12930	800-900	-2.9	
1	109° 0'39"	42°38'31"	3347	-	0	Granitic till	lateral moraine	Alpine grassland	Typic Haplocryoll	14500	800-900	-2.9	
Stough Creek Basin													
12	109° 0'27"	42°37'40"	3475	-	0	Granitic till	end moraine	Alpine grassland	Typic Cryorthent	1500	800-900	-3.7	Dahms, 2002
10	108°59'59"	42°37'58"	3414	-	0	Granitic till	kame terrace/lateral moraine	Alpine grassland	Typic Haplocryoll	22000	800-900	-3.3	
Roaring Fork Pass													
2	108°59'58"	42°39'19"	3347	-	0	Granitic till	lateral moraine	Alpine grassland	Typic Haplocryoll	22000	800-900	-2.9	Dahms, 2002
Pete's Lake Road													
1	108°53'15"	42°43'40"	2640	-	0	Granitic till	lateral moraine	Limber pine - common juniper	Ustic Argicryoll	130000	600	1.2	Dahms, 2004; Fabel et al., 2004
2	108°53'8"	42°43'36"	2579	-	0	Granitic till	laterial moraine	Limber pine - common juniper	Ustic Haplocryoll	22000	550	1.4	
Fairfield Creek													
5	108°51'13"	42°44'8"	2329	-	0	Granitic till	lateral moraine	Limber pine, juniper, sagebrush	Ustic Argicryoll	65000	500	2.6	Dahms, 2004; Fabel et al., 2004
2	108°51'28.5"	42°44'10"	2426	-	0	Granitic till	lateral moraine	Limber pine, juniper,	Ustic Argicryoll/Palecryoll	630000	500	2.0	

								sagebrush					
Deer Spring													
1	108°48'48"	42°44'7"	2304	-	0	Granitic till	lateral moraine	Sagebrush, fescue, wheatgrass	Ustic Argicryoll/Palecryoll	850000	500	3.2	Dahms, 2004; Fabel et al., 2004
Table Mountain													
1	108°45'36"	42°45'20"	2225	-	0	Granitic till	unidentified till feature	Sagebrush, fescue, wheatgrass	Ustic Argicryoll/Palecryoll	1200000	450	3.4	Dahms, 2004

Table 2
Click here to download Table: Table2.doc

Table 2. Characterstics of the Alpine sites.

Site / soil profile	Longitude °E	Latitude °N	Elevation m asl	Aspect °N	Slope %	Parent material	Location	Vegetation	Soils (Soil taxonomy; Soil Survey Staff, 2010)	Soil age y	MAP mm/y	MAT °C	Source
Val di Rabbi													
S1	10° 27'36"	46° 13'42"	2100	60	32	Paragneiss till	Lateral moraine	European larch, common Juniper	Typic Haplocryod	17300	1300	1.5	Favilli et al., 2009
S2	10° 27'29"	46° 13'39	2230	70	55	Paragneiss till	Lateral moraine	Rhododendron, dwarf shrubs, alpine grassland	Typic Haplocryod	11100	1300	0.7	
S3	10° 28'34"	46° 13'30	2380	320	5	Paragneiss till	Lateral moraine	Alpine grassland	Typic Cryorthent	10750	1300	0	
S4	10° 28'33"	46° 13'29	2370	300	10	Paragneiss till	Solifluction, ground moraine	Alpine grassland	Typic Cryorthent	8860	1300	0	
S5	10° 27'36"	46° 13'42	2083	240	32	Paragneiss till	Lateral moraine	European larch, common Juniper	Typic Haplocryod	10840	1300	1.5	
S6	10° 27'36"	46° 13'44	2076	5	38	Paragneiss till	Lateral moraine	European larch, common Juniper	Typic Haplocryod	4730	1300	1.6	
S7	10° 27'29"	46° 13'44	2100	3	43	Paragneiss till	Lateral moraine	European larch, common Juniper	Typic Haplocryod	5450	1300	1.5	
S8	10° 26'18"	46° 13'54	2552	200	33	Paragneiss till	Inactive rockglacier	Alpine grassland	Humic Dystrocryept	9200	1300	-1.1	
S9	10° 26'20"	46° 13'48	2449	90	0	Paragneiss till	Recessional moraine	Alpine grassland	Typic Haplocryod	11200	1300	-0.4	
Morteratsch													
S1	9° 56'39"	46° 26'49"	1930	330	10	Granitic till	ground moraine	Green alder scrub	Typic Cryorthent	138	1100	0.7	Mavris et al., 2010
S2	9° 56'41"	46° 26'52"	1930		15	Granitic till	ground moraine	Green alder scrub	Typic Cryorthent	128	1100	0.7	Egli et al., 2003;
S3	9° 56'36"	46° 26'44"	1930	280	<5	Granitic till	ground moraine	Epilobietum fleischeri with	Typic Cryorthent	108	1100	0.7	Maisch et al., 2005

								single willow shrubs and Alpenrose					
S4	9° 56'36"	46° 26'42"	1935	320	<5	Granitic till	ground moraine	Epilobietum fleischeri with single willow shrubs and Alpenrose	Typic Cryorthent	98	1100	0.7	
S5	9° 56'28"	46° 26'33'	1950	30	<5	Granitic till	ground moraine	Pioneer grass communities	Typic Cryorthent	68	1100	0.7	
S6	9° 56'25"	46° 26'16'	2015	330	<5	Granitic till	ground moraine	Epilobietum fleischeri with single willow shrubs and Alpenrose	Typic Cryorthent	48	1100	0.3	
S7	9° 56'06"	46° 26'13"	2015	260	<5	Granitic till	ground moraine	Pioneer grass communities	Typic Cryorthent	48	1100	0.3	
S8	9° 56'07"	46° 26'20"	1990	150	<5	Granitic till	ground moraine	Pioneer grass communities	Typic Cryorthent	58	1100	0.5	
S9	9° 56'08"	46° 26'25"	2000	30	<5	Granitic till	ground moraine	Pioneer grass communities	Typic Cryorthent	73	1100	0.4	
S10	9° 56'13"	46° 26'33"	1980	60	<5	Granitic till	ground moraine	Epilobietum fleischeri with single willow shrubs and Alpenrose	Typic Cryorthent	78	1100	0.5	
A	9°56'38"	46°26'50	1930	330	10	Granitic till	Lateral moraine	Green alder scrub	Typic Cryorthent	150	1100	0.7	
AC	9°56'27"	46°26'55"	1920	320	10	Granitic till	Lateral moraine	Larch, Scots pine	Typic Dystrocryept	1300	1100	0.8	
AP	9°57'03"	46°27'02"	2030	350	10	Granitic till	Lateral moraine	Larch, Scots pine	Typic Haplocryod	12500	1100	0.5	
Schmadri													
	7°52'36	46°30'17"	2030	350	<5	Granitic till	Lateral moraine	Alpine grassland	Typic Haplocryod	3500	2000	0.5	Egli et al., 2001;
	7°52'46"	46°30'26"	2020	10	<5	Granitic till	Lateral moraine	Alpine grassland	Typic Haplocryod	11500	2000	0.5	Wipf, 2001
Val Mulix													

	S1	9° 44'50"	46° 34'56"	2100	35	11	Granitic till	Lateral moraine	Larch, Swiss pine, heath	Typic Haplocryod	14900	1250	-1.1	Böhlert et al., 2011;
	S2	9° 45'07"	46° 34'35"	2060	0	16	Granite	lower rock glacier lobe	Alpine grassland	Typic Haplocryod	10000	1250	-0.8	Maisch, 1981
	S3	9° 45'13"	46° 34'41"	2150	315	9	Granitic till	Lateral moraine	Alpine grassland	Typic Haplocryod	10700	1250	-1.3	
	S4	9° 45'11"	46° 34'30"	2130	300	8	Granite	middle rock glacier lobe	Alpine grassland	Typic Haplocryod	9600	1250	-1.2	
	S5	9° 45'16"	46° 34'29"	2280	300	6	Granite	upper rock glacier lobe	Alpine grassland	Typic Haplocryod	8600	1250	-2	
Meggerwald														
		8°22′17	47°03′39"	620	325	< 10	Granitic till	ground moraine	White fir, blueberry, European beech	Typic Haplorthod	19200	1300	7.5	Hantke, 1983; Keller and Krayss, 1993; Maisch, 2000;
		8°22′29"	47°03′31"	614	325	< 10	Granitic till	ground moraine	White fir, blueberry, European beech	Spodic Dystrudept	19200	1300	7.5	Egli et al., 2002; Egli et al., 2010b
Gletsch														
		8° 21'52"	46° 33'53"	1760	-	0	Granitic till	end moraine	Pioneer grass communities	Typic Udorthent	150	2000	1.2	Egli et al., 2001;
		8° 21'50"	46° 33'54"	1760	-	0	Granitic till	end moraine	Pioneer grass communities	Typic Udorthent	260	2000	1.2	Zumbühl and Holzhauser,
		8° 21'46"	46° 33'52"	1760	-	0	Granitic till	end moraine	Alpine grassland	Typic Udorthent	300	2000	1.2	1988
		8° 21'45"	46° 33'51"	1760	-	0	Granitic till	end moraine	Alpine grassland	Typic Dystrudept	450	2000	1.2	
		8° 21'42"	46° 33'49"	1760	-	0	Granitic till	end moraine	Alpine grassland	Typic Dystrudept	700	2000	1.2	
		8° 21'41"	46° 33'48"	1760	-	0	Granitic till	end moraine	Alpine grassland	Typic Dystrudept	3000	2000	1.2	
		8° 21'23"	46° 33'40"	1790	-	0	Granitic till	Lateral moraine	Alpine grassland	Typic Haplorthod	10500	2000	1.2	

Table 3
Click here to download Table: Table3.doc

Table 3. Major IR absorption bands and assignments (Piccolo and Mirabella, 1985; Stevenson, 1994; Guo and Bustin, 1997; Senesi et al., 2003; Tan, 2003).

Band	Wave number cm^{-1}	Assignment
1	2980-2880	Aliphatic C-H stretching (aliphatic methyl and methylene groups)
2	1725-1710	C=O stretching of COOH, aldehydes and ketones
3	1660-1630	C=O stretching of amide groups, quinone C=O and/or C=O of H-bonded conjugated ketones
4	1620-1600	Aromatic C=C, strongly H-bonded C=O of conjugated ketones
5	1535-1500	Aromatic rings, amide II vibrations
6	1495-1470	N-H stretching of proteic amides
7	1470-1440	Aliphatic C-H stretching
8	1413-1333	OH deformation and C-O stretching of phenolic groups
9	1190-1127	C-OH stretching of aliphatic, alcoholic O-H
10	1116-1050	Secondary alcohols
11	1080-1030	C-O stretching of polysaccharide

Table 4
Click here to download Table: Table4.doc

Table 4. C and N in different soil organic matter fractions of the Wind River Range soils: total content, stable fraction (that resists to a H_2O_2 treatment) and labile fraction (oxidised with H_2O_2)

Soil age (y)	Profile	Horizon	Depth (cm)	Soil skeleton (w%)	Bulk density (g/cm^3)	C_{tot} g/kg	N_{tot} g/kg	C_{tot}/N_{tot}	C_{stable} g/kg	N_{stable} g/kg	C_{stable}/N_{stable}	C_{labile} g/kg	N_{labile} g/kg	C_{labile}/N_{labile}
150	BFL 9	Cox	0-5	42	1.35	3.90	0.30	13.0	0.35	0.10	3.6	3.55	0.20	17.3
		Cu1	5-15	56	1.77	5.10	0.20	25.5	0.45	0.20	2.3	4.65	0.00	
		Cu2	15-25	56	1.77	3.10	0.30	10.3	0.40	0.09	4.4	2.70	0.21	12.9
1500	SCB 12	A	0-2	31	1.35	8.61	0.77	11.2	0.55	0.15	3.8	8.06	0.62	12.9
		Cox	2-10	47	1.77	4.70	0.50	9.4	0.93	0.18	5.1	3.77	0.32	11.9
		2Cv	10-30	51	1.77	3.10	0.30	10.3	0.77	0.18	4.2	2.33	0.12	19.9
9930	BFL 6	A	0-10	7	0.98	70.20	5.60	12.5	2.90	0.70	4.1	67.30	4.90	13.7
		2Bt	10-20	29	1.20	23.60	2.20	10.7	0.63	0.55	1.1	22.97	1.65	13.9
		2Cox1	20-28	34	1.54	11.90	1.10	10.8	0.42	0.18	2.3	11.48	0.92	12.5
		2Cox2	28-45	33	1.77	4.00	0.40	10.0	0.41	0.20	2.0	3.59	0.20	18.3
12930	BFL 5	A 0-9	0-9	22	0.94	55.60	4.20	13.2	0.91	0.34	2.7	54.69	3.86	14.2
		2Bt	9-22	31	1.26	30.50	2.70	11.3	0.92	0.55	1.7	29.58	2.15	13.8
		2Cox1	22-55	32	1.62	5.20	0.40	13.0	0.48	0.09	5.5	4.72	0.31	15.1
		2Cox2	55-75	46	1.77	2.00	0.20	10.0	0.39	0.06	6.1	1.61	0.14	11.8
14500	BFL 1	A	0-8	8	1.21	72.80	6.00	12.1	2.15	0.35	6.1	70.65	5.65	12.5
		Bt	8-18	20	1.27	28.10	2.50	11.2	1.19	0.54	2.2	26.91	1.96	13.7
		2BC	18-28	40	1.32	5.40	0.50	10.8	0.46	0.09	5.3	4.94	0.41	12.0
		2Cox1	27-65	43	1.45	5.60	0.50	11.2	1.25	0.18	6.9	4.35	0.32	13.7
		2Cox2	65-90	53	1.77	2.70	0.30	9.0	0.52	0.15	3.6	2.18	0.15	14.2
16000	SCB 10	A	0-6	3	0.96	168.10	12.20	13.8	12.64	0.75	16.8	155.46	11.45	13.6
		Ej	6-7	3	1.10	99.83	8.22	12.1	6.21	1.14	5.5	93.62	7.08	13.2

		Bw	7-11	4	0.97	113.70	9.50	12.0	7.43	1.09	6.8	106.27	8.41	12.6
		2ABb	11-23	17	1.01	55.90	4.80	11.6	1.66	1.01	1.6	54.24	3.79	14.3
		2Btb	23-29	22	1.20	12.30	1.20	10.3	0.47	0.15	3.1	11.83	1.05	11.3
		3Cox1b	29-75	37	1.54	5.40	0.50	10.8	0.50	0.08	6.2	4.90	0.42	11.7
		3Cox2b	75-85	46	1.77	2.90	0.30	9.7	0.62	0.07	8.6	2.28	0.23	10.0
16000	RFP 2	A	0-13	6	1.03	73.20	5.70	12.8	4.67	0.83	5.6	68.53	4.87	14.1
		2Bt1	13-23	17	1.17	18.30	1.70	10.8	0.75	0.48	1.6	17.55	1.22	14.4
		2Bt2	23-50	35	1.34	11.20	1.00	11.2	0.77	0.23	3.3	10.43	0.77	13.6
		2BC	50-60	33	1.54	3.50	0.30	11.7	0.41	0.07	5.6	3.09	0.23	13.6
		2Cox	60-75	42	1.77	4.20	0.30	14.0	0.47	0.08	5.8	3.73	0.22	17.1
22000	PLR 2	A	0-10	20.5	1.26	27.90	2.10	13.3	1.15	0.34	3.4	26.75	1.76	15.2
		AB	10-20	23.1	1.35	16.60	1.30	12.8	1.11	0.22	5.0	15.49	1.08	14.4
		BW	20-30	40.7	1.45	7.40	0.60	12.3	0.00	0.00		7.40	0.60	12.3
		Cox	30-50	41.6	1.77	3.10	0.20	15.5	0.36	0.05	6.8	2.74	0.15	18.6
		2C	> 50	52.8	1.83	1.60	0.10	16.0	0.51	0.05	9.5	1.09	0.05	23.7
65000	FC5	A	0-7	16.2	1.26	82.84	6.39	13.0	2.08	0.17	12.4	80.76	6.22	13.0
		Bt1	7-25	27.3	1.54	10.41	0.92	11.3	0.88	0.08	11.3	9.53	0.84	11.3
		2Bt2	25-50	26.3	1.59	3.60	0.32	11.3	0.60	0.03	20.3	3.00	0.29	10.3
		2Coxx	50-85	32.5	1.77	2.67	0.21	12.7	0.54	0.04	13.8	2.13	0.17	12.5
		2C	> 85	39.6	1.83	1.19	0.08	14.9	0.79	0.03	27.3	0.40	0.05	7.8
130000	PLR1	A	0-8	18.4	1.26	30.21	2.65	11.4	2.36	0.25	9.3	27.85	2.40	11.6
		Bt1b	8-30	16.5	1.54	12.54	1.26	10.0	1.16	0.20	5.9	11.38	1.06	10.7
		Bt2b	30-50	12.4	1.59	8.06	0.89	9.1	1.33	0.20	6.6	6.73	0.69	9.8
		Bt3b	50-85	7.5	1.59	6.12	0.69	8.9	1.10	0.21	5.2	5.02	0.48	10.5
		2Coxb	85-100	53.1	1.77	4.46	0.46	9.7	0.95	0.16	6.1	3.51	0.30	11.6
630000	FC2	A	3-5	20.8	1.07	59.66	4.75	12.6	2.45	0.22	11.1	57.21	4.53	12.6
		Bt1	5-23	18.1	1.41	10.24	0.93	11.0	1.04	0.10	10.8	9.20	0.83	11.0

		2Bt2b	23-45	16.8	1.58	4.86	0.42	11.6	0.66	0.09	7.3	4.20	0.33	12.7
		2Coxb	130-210	14.1	1.77	1.64	0.06	27.3	0.73	0.06	12.1	0.91	0.00	
		2Cb	> 210	7.7	1.83	1.64	0.06	27.3	0.56	0.06	9.3	1.08	0.00	
850000	DS1	A	0-11	14.5	1.31	24.20	2.20	11.0	0.86	0.29	2.9	23.34	1.91	12.2
		Btb1	11-30	20.1	1.47	12.80	1.20	10.7	0.81	0.39	2.1	11.99	0.81	14.9
		2Bt2b	30-150	36.2	1.53	6.00	0.50	12.0	0.43	0.25	1.7	5.57	0.25	22.1
1200000	TM-1	A	0-12	0	1.26	14.30	1.30	11.0	0.63	0.24	2.6	13.67	1.06	12.9
		B	12-20	0.7	1.83	9.10	0.80	11.4	1.01	0.18	5.6	8.09	0.62	13.1
		Bt1b1	20-45	0	1.54	8.90	0.80	11.1	0.81	0.26	3.1	8.09	0.54	15.0
		Bt2b1	45-60	2	1.59	10.20	0.90	11.3	0.90	0.29	3.1	9.30	0.61	15.2
		Coxb1	65-85	1.2	1.77	6.10	0.50	12.2	0.47	0.11	4.4	5.63	0.39	14.3
		ABb2	85-115	5.2	1.26	14.20	1.20	11.8	1.75	0.43	4.1	12.45	0.77	16.2
		Bt1b2	115-150	17.9	1.54	8.50	0.80	10.6	0.88	0.28	3.1	7.62	0.52	14.8
		Bt2b2	150-200	18.4	1.54	6.70	0.30	22.3	0.80	0.19	4.2	5.90	0.11	54.5
		Bt3b2	200-300	11.6	1.59	3.80	0.30	12.7	0.72	0.11	6.8	3.08	0.19	15.8
		Cox1b2	300-400	18.5	1.77	2.20	0.20	11.0	1.43	0.16	8.7	0.77	0.04	21.7
		Cox2b2	400-500	16.1	1.77	2.70	0.20	13.5	0.83	0.20	4.2	1.87	0.00	

Table 5

Table 5. C and N in different soil organic matter fractions of the soils of the European Alps: total content, stable fraction (that resists to a H_2O_2 treatment) and labile fraction (oxidised with H_2O_2)

Site/ Profile	Soil age (y)	Horizon	Depth (cm)	Soil skeleton (w%)	Bulk density (g/cm^3)	C_{tot} g/kg	N_{tot} g/kg	C_{tot}/N_{tot}	C_{stable} g/kg	N_{stable} g/kg	C_{stable}/N_{stable}	C_{labile} g/kg	N_{labile} g/kg	C_{labile}/N_{labile}
Val di Rabbi														
S1	17300	AE	0-4	5	0.90	103.7	5.70	18.2	6.05	0.84	7.2	97.7	4.86	20.1
		BE	4-8	34	0.91	61.0	2.90	21.0	10.49	0.84	12.5	50.5	2.06	24.5
		Bs1	8-20	10	0.74	39.4	1.80	21.9	2.06	0.65	3.2	37.3	1.15	32.5
		Bs2	20-45	51	1.16	16.8	0.70	24.0	4.75	0.54	8.9	12.0	0.16	73.5
		BC	45-60	34	1.41	7.5	0.60	12.5						
S2	11100	AE	0-9	3	0.92	184.6	28.10	6.6	30.32	0.46	65.6	154.3	27.64	5.6
		Bhs	9-20	19	1.01	63.8	11.80	5.4						
		Bs	20-40	58	1.40	25.4	8.80	2.9	2.83	0.47	6.1	22.6	8.34	2.7
S3	10750	AE1	0-4	8	0.91	124.9	6.80	18.4	15.35	0.84	18.4	109.6	5.96	18.4
		AE2	4-12	21	0.95	48.0	2.20	21.8						
		Bhs	12-20	45	1.25	71.4	3.10	23.0	5.59	0.52	10.8	65.8	2.58	25.5
S4	8860	A	0-8	0	0.93	55.3	3.80	14.6						
		Bw1	8-20	1	0.93	20.7	1.50	13.8						
		Bw2	20-32	32	0.78	19.5	1.30	15.0						
		Ab	32-35	2	0.82	62.0	3.90	15.9						
		Bbw	35-40	49	1.36	9.1	0.50	18.2						
S5	10840	AE	0-11	7	0.90	56.2	2.70	20.8	1.97	0.63	3.1	54.2	2.07	26.2
		Bs1	11-26	16	1.01	34.9	1.70	20.5	5.20	1.04	5.0	29.7	0.66	45.0
		Bs2	26-50	47	1.46	22.5	1.10	20.5	4.61	0.53	8.7	17.9	0.57	31.5
S6	4730	AE	8-17	54	0.86	76.5	4.10	18.7	5.77	0.63	9.1	70.7	3.47	20.4
		Bs1	17-38	67	1.27	45.3	1.80	25.2	5.80	0.34	17.1	39.5	1.46	27.1
		Bs2	38-45	68	1.26	47.6	1.60	29.8	7.77	0.23	33.3	39.8	1.37	29.1
		BC	45-60	56	1.18	35.5	1.10	32.3						
S7	5450	AE	5-10	43	0.90	143.9	6.40	22.5	7.43	0.78	9.5	136.5	5.62	24.3
		Bs1	11-25	63	1.30	48.5	1.40	34.6						
		Bs2	25-50	44	1.40	48.3	1.60	30.2	11.78	0.47	25.1	36.5	1.13	32.3
		BC	50-60	60	1.45	48.7	1.50	32.5						
S8	9200	AE	0-20	37	0.92	43.0	2.30	18.7	4.60	0.62	7.5	38.4	1.69	22.8
		Bs	20-25	59	1.10	29.5	1.40	21.1						

		BC	25-48	54	1.35	8.0	0.50	16.0	1.24	0.15	8.4	6.8	0.35	19.2
S9	11200	AE	0-11	16	0.90	56.4	3.80	14.8	1.78	0.83	2.1	54.6	2.97	18.4
		Bs	11-23	27	1.20	37.8	1.60	23.6	1.66	0.44	3.8	36.1	1.16	31.2
		BC	23-40	46	1.40	17.9	0.70	25.6	1.51	0.22	6.9	16.4	0.48	34.0
Morteratsch														
S1	138	O	0-6	41	0.20	321.1	12.22	26.3	1.20	0.14	8.6	319.9	12.08	26.5
		A	6-9	50	1.60	6.2	0.32	19.4	1.20	0.14	8.6	5.0	0.18	27.8
		BC	9-14	53	1.60	3.7	0.22	16.8						
		C	14-30	40	1.80	2.8	0.12	23.3						
S2	128	A	0-10	64	1.40	13.8	0.76	18.2	0.80	0.09	8.9	13.0	0.67	19.4
		AC	10-40	68	1.50	4.8	0.26	18.5						
S3	108	A	0-3	54	1.10	28.1	1.58	17.8	1.50	0.25	6.0	26.6	1.33	20.0
		AC	3-15	70	1.70	3.9	0.23	17.0						
S4	98	A	0-1	55	0.80	56.0	3.10	18.1	3.50	0.25	14.0	52.5	2.85	18.4
		AC	1-5	51	1.70	4.2	0.25	16.8						
		C	5-30	70	1.60	1.8	0.08	22.5						
S5	68	A1	0-1	7	0.80	40.3	1.34	30.1	0.90	0.10	9.0	39.4	1.24	31.8
		A2	1-4	1	1.50	5.0	0.22	22.7	0.90	0.10	9.0	4.1	0.12	34.2
		C1	4-9	36	1.40	2.5	0.15	16.7						
		C2	9-20	64	1.80	3.7	0.21	17.6						
S6	48	A	0-3	64	1.60	37.5	1.69	22.2	3.40	0.22	15.5	34.1	1.47	23.2
		C	3-25	68	1.70	2.1	0.13	16.2						
S7	48	A	0-4	26	1.40	60.2	5.20	11.6	6.20	0.31	20.0	54.0	4.89	11.0
		C1	4-11	37	1.60	2.8	0.22	12.7						
		C2	11-34	67	2.00	3.7	0.28	13.2						
S8	58	OA	0-12	63	1.00	118.2	6.32	18.7	5.30	0.47	11.3	112.9	5.85	19.3
		C	12-33	48	1.80	3.1	0.22	14.1						
S9	73	O	0-3	44	0.50	147.8	8.96	16.5	7.10	0.33	21.5	140.7	8.63	16.3
		AC	3-10	65	1.50	4.8	0.30	16.0	0.30	0.07	4.3	4.5	0.23	19.6
		C	10-36	58	1.70	3.3	0.22	15.0						
S10	78	A1	0-2	49	0.60	53.4	2.73	19.6	1.90	0.18	10.6	51.5	2.55	20.2
		A2	2-10	68	1.70	5.2	0.23	22.6	0.50	0.12	4.2	4.7	0.11	42.7
		AC	10-25	84	1.70	4.3	0.21	20.5						
AS22	30	(A)C	0-4	53	1.40	2.9	0.30	9.7	0.39	0.05	8.0	2.5	0.25	10.0
AS23	30	(A)C	0-4	66	1.40	2.6	0.24	10.8	0.42	0.06	7.3	2.2	0.18	11.9
AS24	20	(A)C	0-4	77	1.40	2.9	0.39	7.4	0.76	0.06	12.8	2.1	0.33	6.5

AS28	3	(A)C	0-4	75	1.40	1.9	0.73	2.6	0.49	0.06	8.2	1.4	0.67	2.1
AS29	3	(A)C	0-4	72	1.40	2.1	0.26	8.1	0.42	0.08	5.4	1.7	0.18	9.2
A	150	A	0-7	65	1.40	34.3	2.50	13.7						
		(B)A	7-25	59	1.90	3.7	0.30	12.3						
		C	>25	64	1.90	2.5	0.20	12.5						
AC	1300	A	0-7	65	1.43	34.3	2.40	14.3	2.47	0.20	12.5	31.8	2.20	14.4
		A(Bw)	10-20	59	1.86	3.7	0.30	12.3	1.49	0.15	9.8	2.2	0.15	14.9
		C	35-40	64	1.90	2.5	0.20	12.5	1.15	0.16	7.1	1.4	0.04	35.1
AP	12500	O	0-5	14	0.80	176.4	6.50	27.1						
		E	5-15	30	1.34	16.4	0.70	23.4						
		Bs1	15-25	55	1.54	8.9	0.50	17.8						
		Bs2	40-60	57	1.67	1.7	0.00							
		BC	70-80	53	1.71	0.0	0.00							
		C	110-120	67	1.74	0.0	0.00							
Schmadri														
	3300	O	3-8	0	0.57	142.8	8.70	16.4	4.89	0.85	5.7	137.9	7.85	17.6
		E	9-14	25	0.77	69.1	3.20	21.6	2.39	0.48	5.0	66.7	2.72	24.5
		Bhs	16-21	27	1.36	112.6	4.40	25.6	3.82	0.52	7.4	108.8	3.88	28.0
		Bs	28-38	72	1.76	45.5	1.70	26.8	4.57	0.20	22.8	40.9	1.50	27.3
		C	75-85	79	1.89	6.0	0.10	60.0						
	11500	O	3-10	0	0.39	383.3	18.00	21.3						
		E	10-16	7	1.09	22.3	0.80	27.9						
		Bhs	16-22	23	1.01	113.1	4.80	23.6						
		Bs	24-30	25	0.94	42.6	1.50	28.4						
		BC	55-60	26	1.54	9.5	0.20	47.5						
		C	105-115	42	1.70	2.2	0.00							
Val Mulix														
S1	14900	O	0-13	3	0.37	202.8	8.60	23.6						
		E	13-20	29	0.88	45.9	1.50	30.6						
		Bhs	20-23	21	0.90	50.5	2.00	25.3						
		Bsm	23-50	61	1.75	28.3	0.90	31.4						
		BC	50-70	53	1.68	3.9	0.20	19.5						
		C	>70	61	1.75	2.3	0.30	7.7						

S2	10000	OE	0-7	27	1.24	151.2	5.80	26.1
		Bs	7-40	75	1.53	17.7	0.40	44.3
		Bsm	40-60	69	1.73	43.4	1.10	39.5
		C	>60	79	1.93	4.2	0.20	21.0
S3	10700	O1	0-5	26	0.50	305.1	16.20	18.8
		O2	5-10	17	0.49	189.9	5.00	38.0
		E	10-12	30	0.57	95.3	2.60	36.7
		Bhs	12-14	27	0.69	94.9	3.10	30.6
		Bs	14-26	50	0.81	44.8	1.20	37.3
		BC	26-60	68	1.36	3.5	0.20	17.5
S4	9600	O	0-9	2	0.24	278.3	12.00	23.2
		OE	9-18	6	0.40	171.3	6.00	28.6
		Bs	18-30	57	1.32	75.9	2.60	29.2
		BC	30-50	66	1.37	33.0	1.40	23.6
		C	>50	75	1.51	11.3	0.50	22.6
S5	8600	O1	0-5	3	0.33	328.6	14.30	23.0
		O2	5-10	12	0.33	240.1	8.40	28.6
		E	10-15	37	0.70	23.7	0.50	47.4
		Bhs	15-25	67	0.83	88.2	3.40	25.9
		Bs	25-35	64	1.19	46.3	1.40	33.1
		BC	>35	73	1.54	9.9	0.40	24.8
Meggerwald								
	19200	E	5-15	2	0.71	36.0		
		Bhs	15-40	9	0.75	89.0		
		Bw	40-65	27	1.50	19.0		
		BC	70-90	5	1.54	3.0		
		2C	150-160	42	1.39	2.0		
	19200	A	0-20	13	0.87	35.0		
		Bw1	20-40	20	1.11	11.0		
		Bw2	40-80	26	1.42	6.0		
		BC	80-130	9	1.59	2.0		
		2C	>130	0	1.59	0.0		
Gletsch								

150	A	0 - 5	30	1.02	25.7	1.10	23.4						
	AC	5 - 15	44	1.30	4.4	0.20	22.0						
	C	15 - 25	38	1.20	1.5	0.00							
	C	25 - 35	33	1.30	0.0	0.00							
260	A	0 - 5	35	0.91	38.6	2.40	16.1						
	BC	5 - 15	59	1.22	6.7	0.50	13.4						
	BC	15 - 25	45	1.24	3.1	0.20	15.5						
	(B)C	25 - 35	41	1.37	2.6	0.20	13.0						
	C	35 - 45	50	1.53	1.3	0.00							
300	A	0 - 5	29	0.40	98.2	6.10	16.1	5.40	0.13	40.8	92.8	5.97	15.6
	BC	5 - 15	57	1.45	9.0	0.70	12.9	0.58	0.12	5.0	8.4	0.58	14.4
	BC	15 - 25	61	1.63	3.2	0.30	10.7	0.28	0.08	3.6	2.9	0.22	13.1
	(B)C	25 - 35	71	1.70	1.6	0.00		0.55			1.0		
	C	35 - 45	73	1.70	2.1	0.10	21.0						
450	A	0 - 5	52	0.63	114.6	7.90	14.5	2.39	0.20	12.1	112.2	7.70	14.6
	B	5 - 15	56	1.04	16.8	1.30	12.9	0.42	0.13	3.1	16.4	1.17	14.1
	B	15 - 25	63	1.01	5.4	0.40	13.5	0.29	0.06	5.0	5.1	0.34	15.0
	BC	25 - 35	65	1.40	2.3	0.10	23.0	0.37	0.05	7.6	1.9	0.05	37.6
	C	35 - 45	41	1.51	0.0	0.00							
700	A	0 - 5	49	0.47	120.5	9.00	13.4						
	Bw	5 - 15	42	1.01	10.8	1.00	10.8						
	Bw	15 - 25	42	1.00	5.9	0.50	11.8						
	B	25 - 35	38	1.11	4.0	0.40	10.0						
	BC	35 - 45	30	1.12	4.0	0.30	13.3						
3000	Ah	0 - 5	11	0.21	133.0	6.20	21.5						
	Bw	5 - 15	34	0.71	35.0	2.30	15.2						
	Bw	15 - 25	53	0.92	30.4	1.10	27.6						
	bBw	25-35	45	1.20	111.8	4.60	24.3						
	bBw	35-45	83	1.70	103.8	4.50	23.1						
10500	O	0 - 10	6	0.60	217.6	13.40	16.2						
	E	10 - 20	51	1.32	13.8	0.80	17.3						
	Bhs	20 - 30	75	1.28	58.7	2.90	20.2						
	Bs	30 - 40	66	1.24	15.9	0.60	26.5						
	Bw	50 - 60	46	1.55	11.0	0.40	27.5						
	BC	95-105	67	1.56	5.1	0.10	51.0						

Table 6
Click here to download Table: Table6.doc

Table 6. Ages (obtained using ^{14}C) of the stable organic carbon (H_2O_2 treated samples) of selected sites of the Wind River Range.

Site	Soil age yr	Depth	Horizon	Treated samples (H_2O_2) uncal BP	$\partial^{13}C$ (‰)	Calibrated ages (y calBP) 1 sigma range	2 sigma range
BFL6	9930	0-10 cm	A	1280 ± 35	-18.1 ± 1.1	1180 - 1271	1095 - 1292
		10-20 cm	2Bt	4490 ± 45	-33.7 ± 1.1	5048 - 5284	4975 - 5305
		28-45 cm	2Cox2	4020 ± 40	-37.6 ± 1.1	4431 - 4525	4415 - 4782
BFL5	12930	0-9 cm	A	3245 ± 35	-30.3 ± 1.1	3402 - 3553	3389 - 3559
		9-22 cm	2Bt	3320 ± 35	-27.1 ± 1.1	3480 - 3584	3463 - 3638
		22-55 cm	2Cox1	6200 ± 45	-44.9 ± 1.1	7011 - 7169	6987 - 7248
BFL1	14500	0-8 cm	A	650 ± 30	-22.2 ± 1.1	564 - 662	556 - 670
		27-65 cm	2Cox1	9395 ± 40	-34.6 ± 1.1	10576 - 10678	10516 - 10720

Figure 1

Click here to download high resolution image

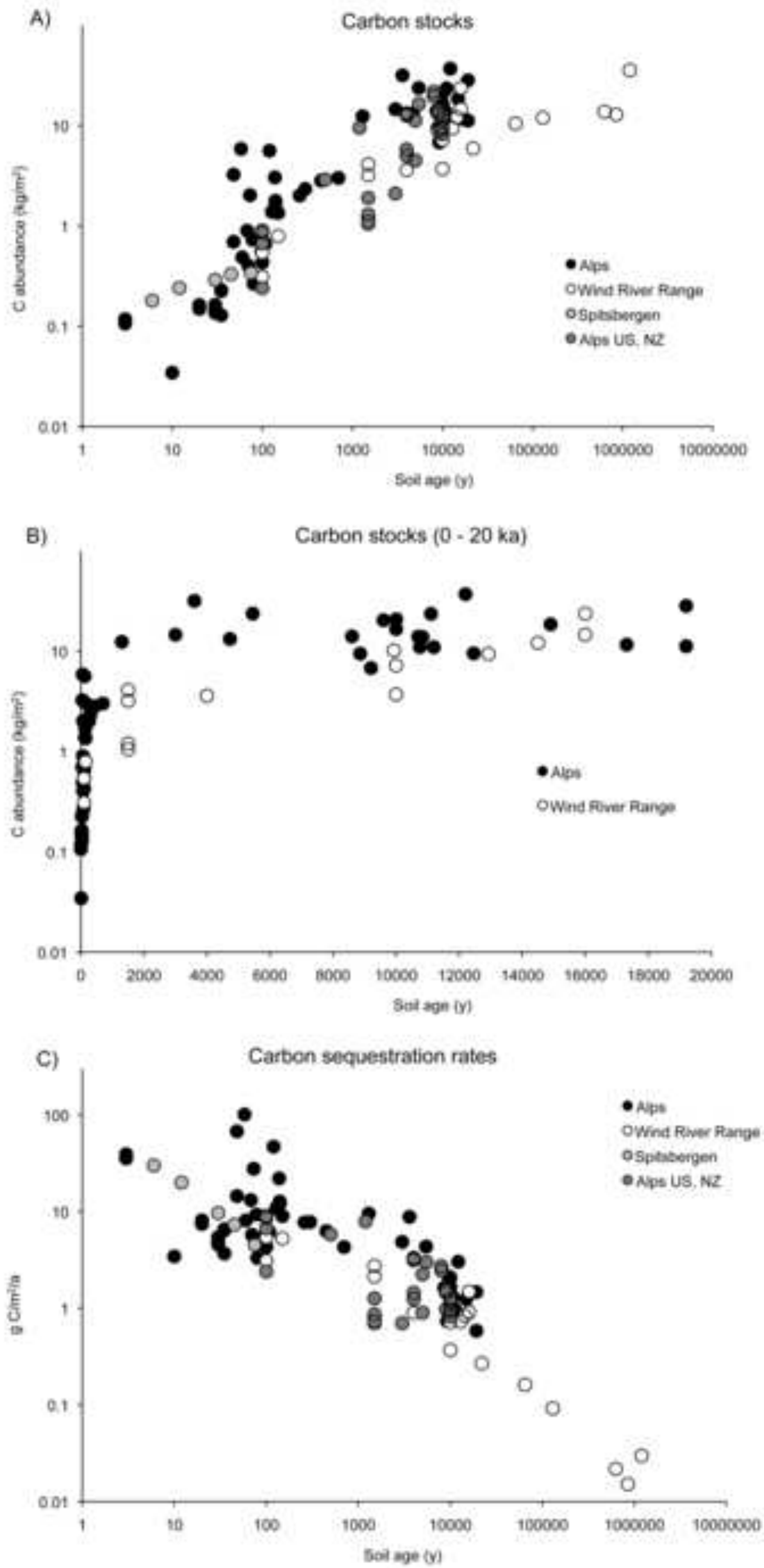


Figure 2

Click here to download high resolution image

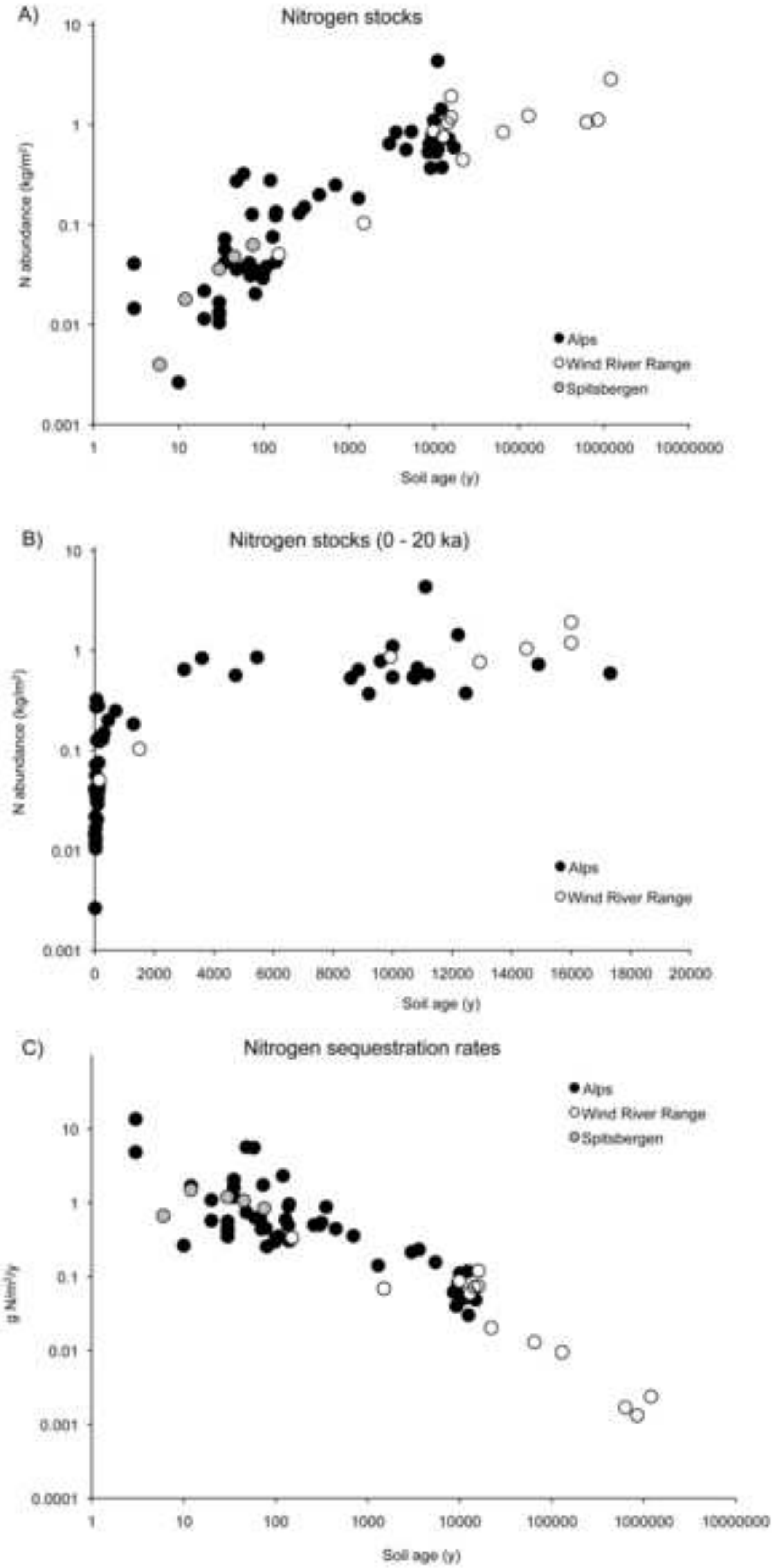


Figure 3

Click here to download high resolution image

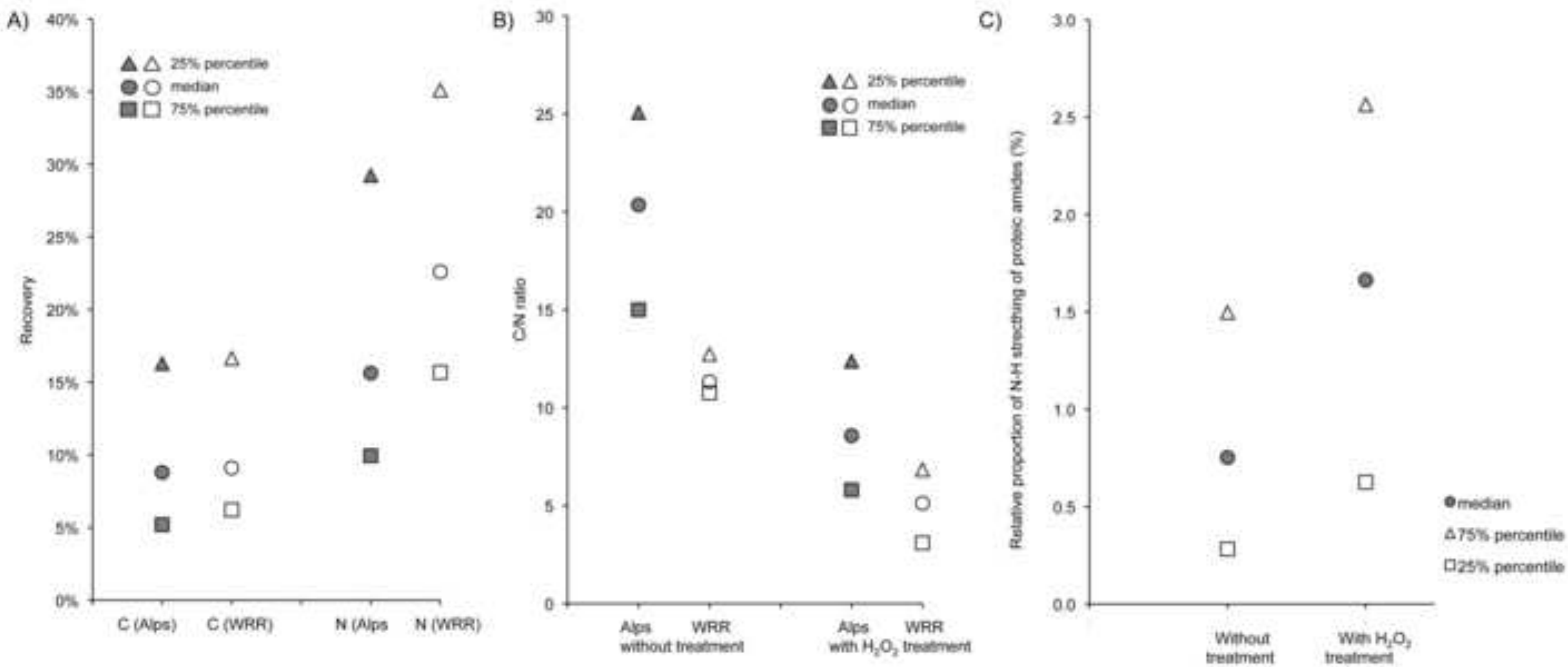


Figure 4
Click here to download high resolution image

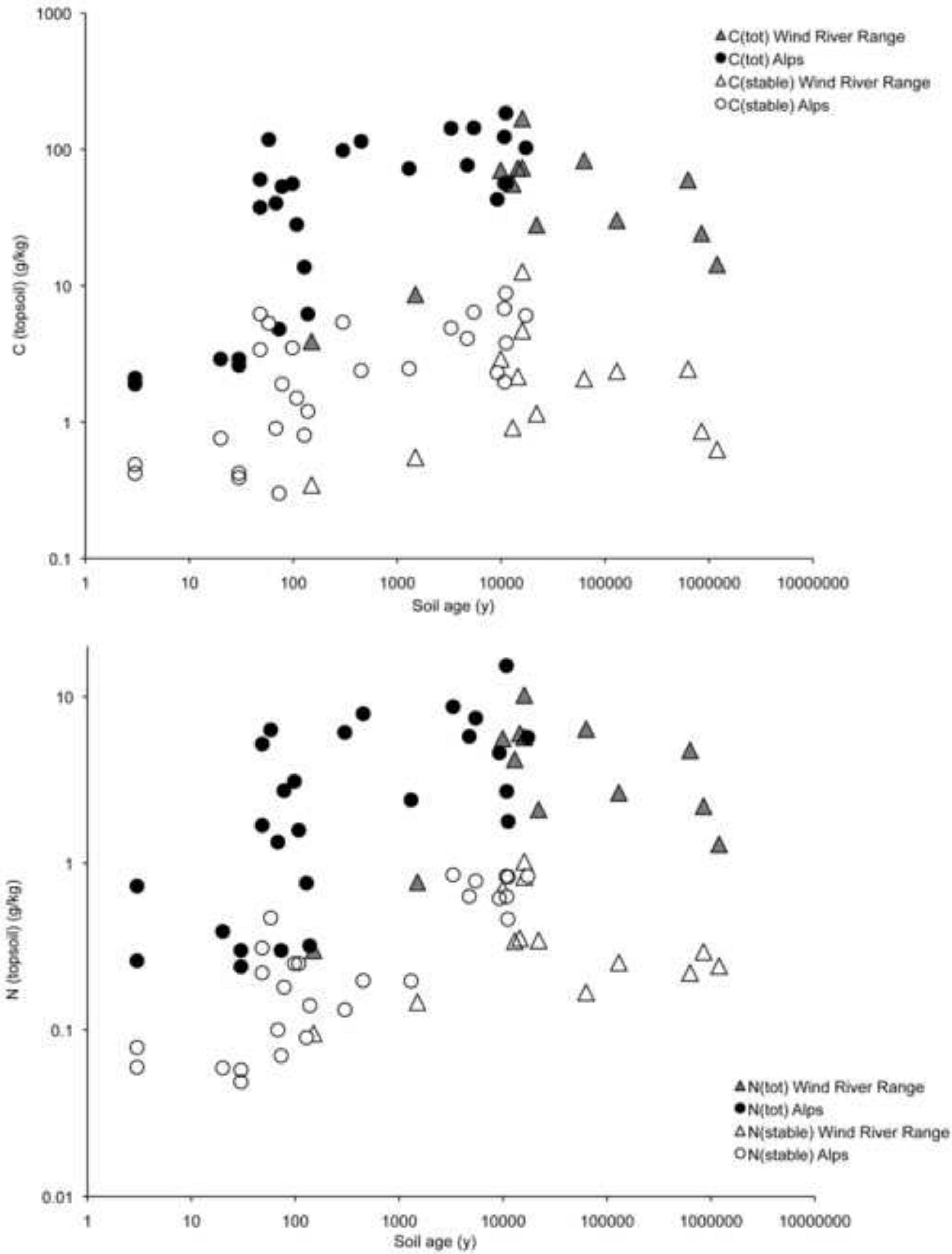


Figure 5
Click here to download high resolution image

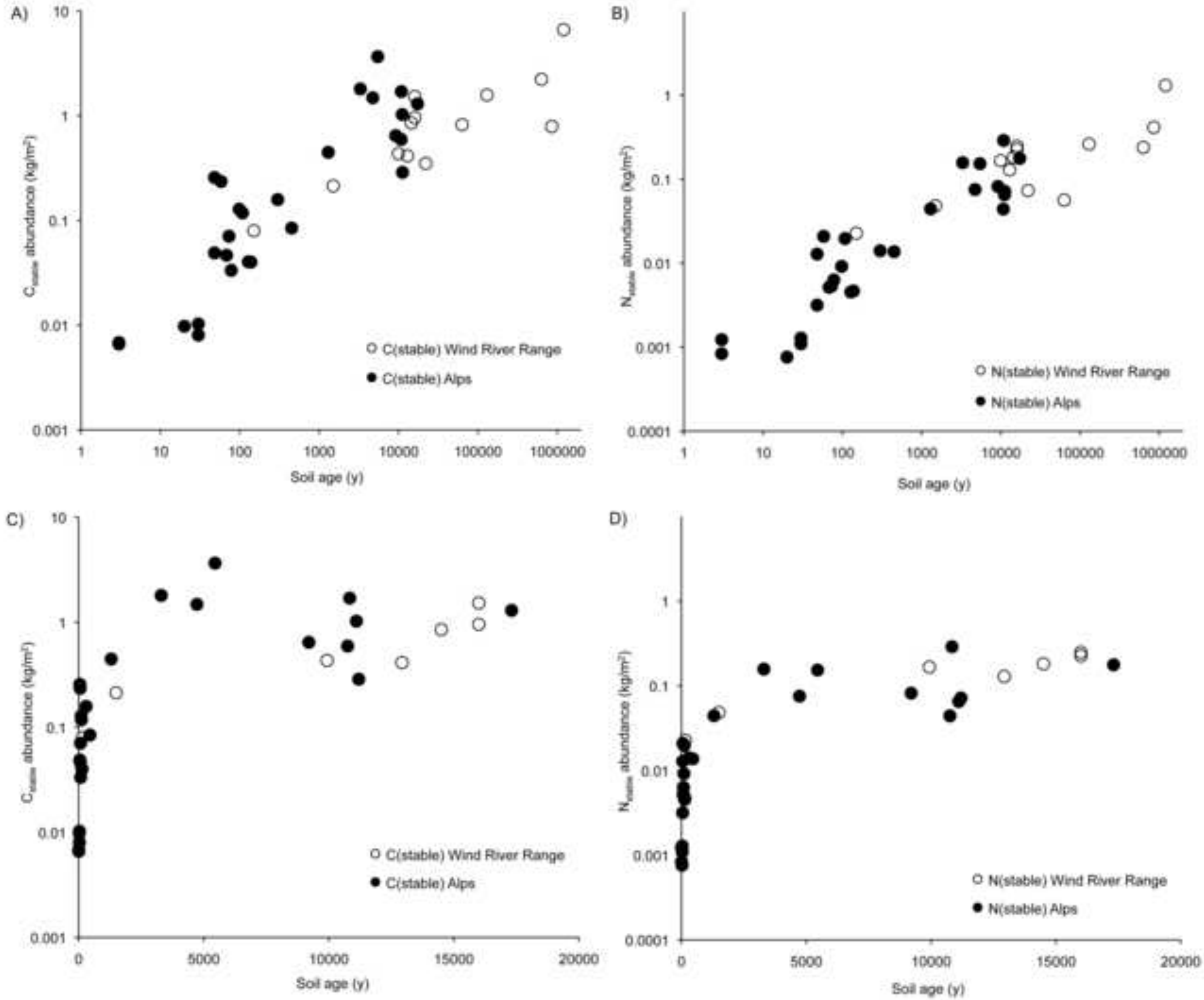
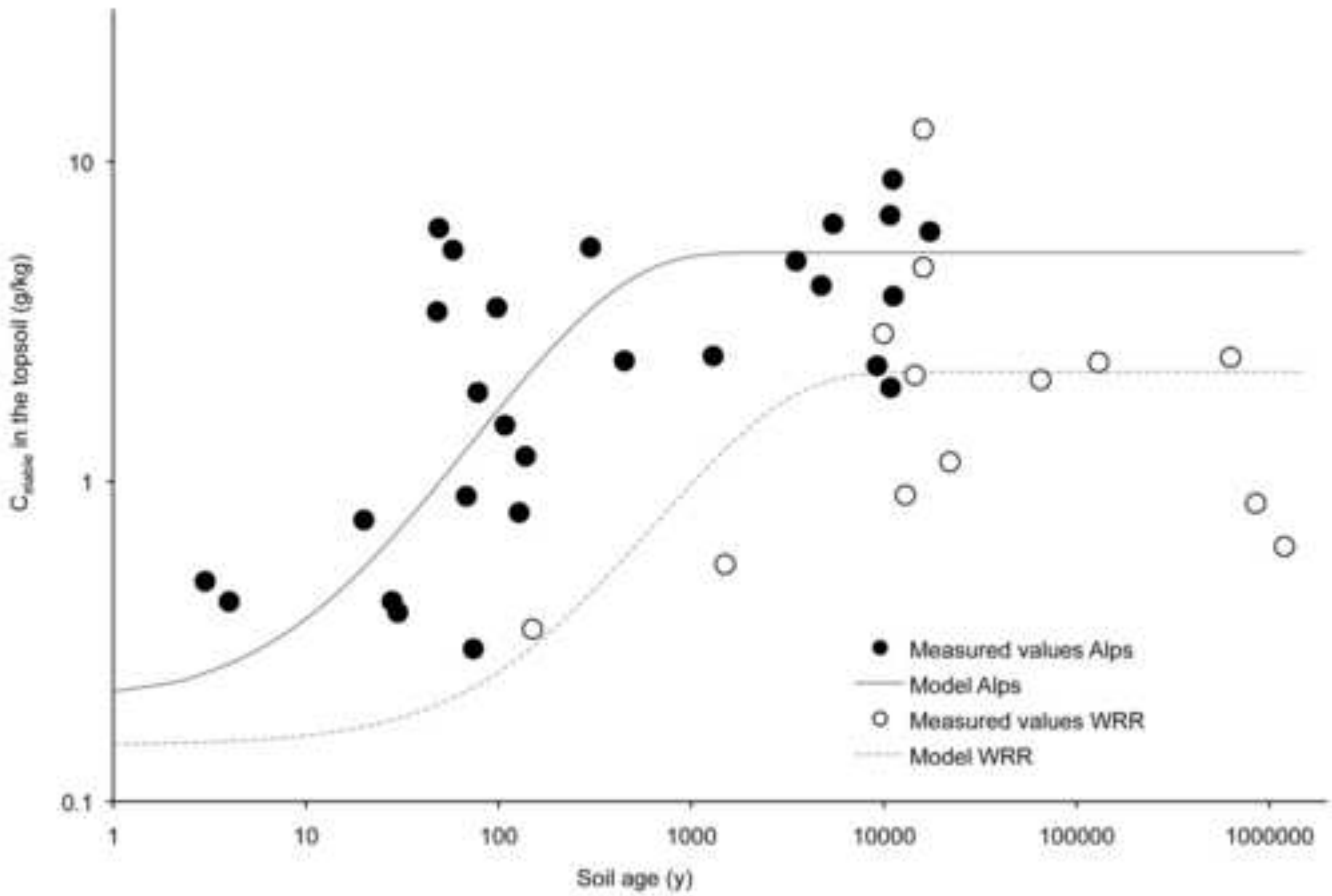


Figure 6
Click here to download high resolution image



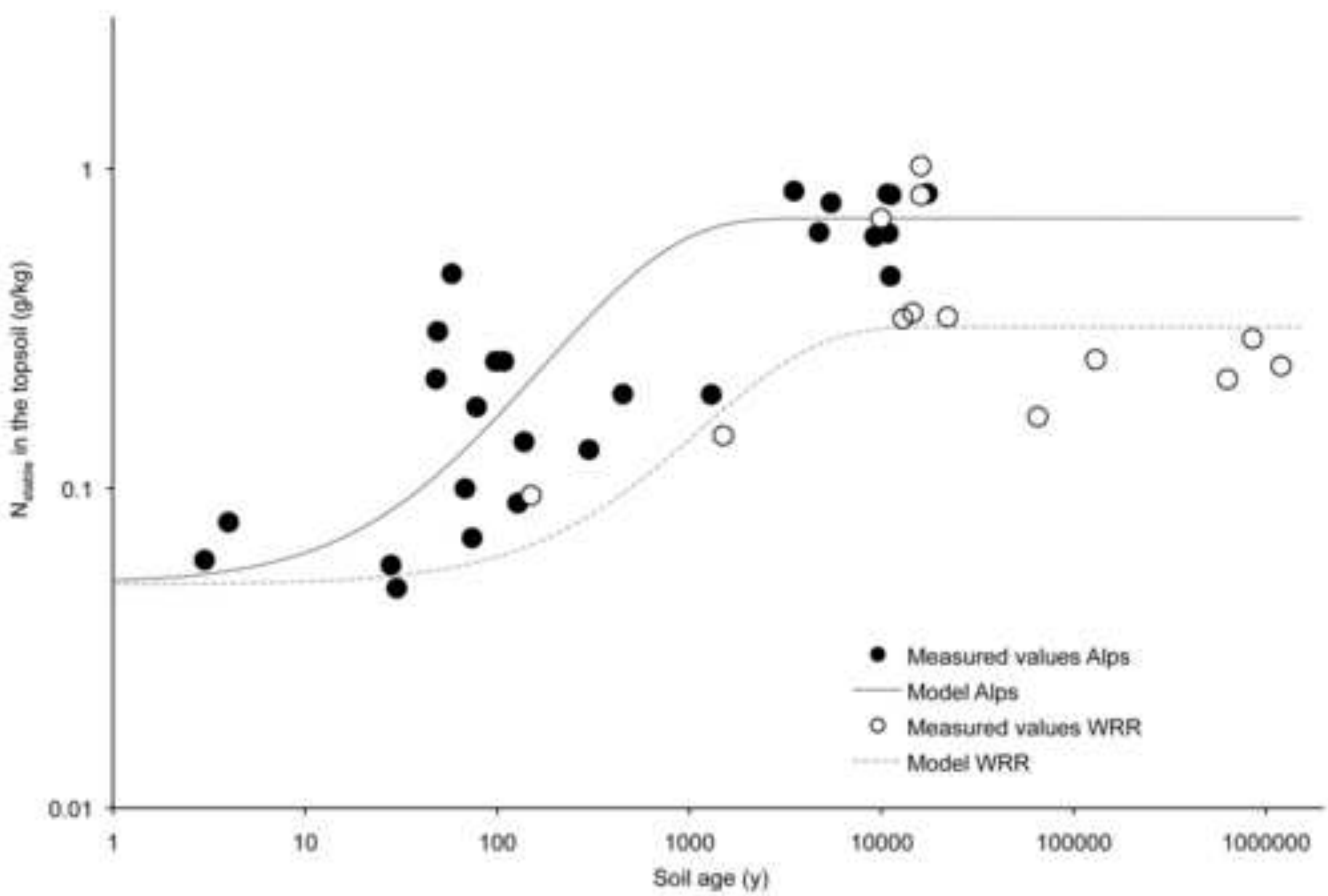


Figure 7

Click here to download high resolution image

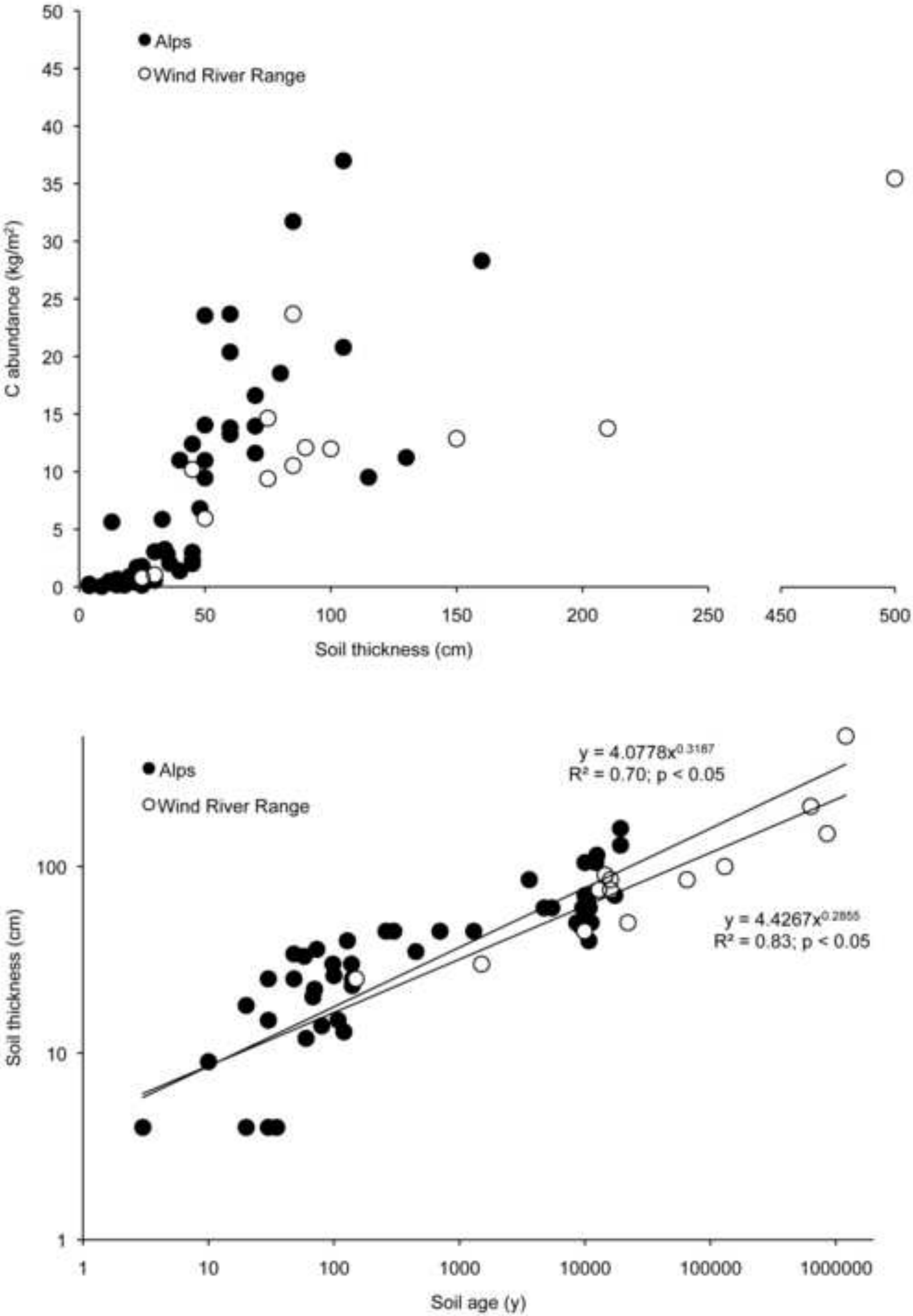


Figure captions

Fig. 1. Abundance and accumulation rate of total soil organic C as a function of time and investigation area. Additionally, org. C datasets from different regions of the Rocky Mountains, the New Zealand Alps (Mahaney, 1974, 1978; Birkeland, 1984; Birkeland et al., 1987, 1989; Bockheim et al., 2000) and Spitsbergen (Kabala and Zapart, 2011) are also considered. A) shows the entire time range; B) focus into the time range 0 – 20ka; only data of the European Alps and the Wind River Range (including the data of Mahaney (1978) and Birkeland et al. (1989) are considered; C) sequestration rates of C.

Fig. 2. Abundance and accumulation rate of total soil organic N as a function of time and investigation area. Additionally, org. N datasets from the Spitsbergen (Kabala and Zapart, 2011) were also considered. A) shows the entire time range; B) focus into the time range 0 – 20 ka, only data of the European Alps and the Wind River Range are considered; C) sequestration rates of N.

Fig. 3. A) Recovery of C and N after the H_2O_2 treatment for the European Alps and the Wind River Range (WRR), B) C/N-ratio with and without H_2O_2 treatment of soil organic matter (Eurpoean Alps and the Wind River Range, WRR) and C) relative proportion of N-H stretching of amide groups with and without any H_2O_2 treatment of the soil samples of the Wind River Range (data for the Alps are in a similar range but exist only for a few sites; see e.g., Egli et al., 2010).

Fig. 4. Concentrations of total and stable C and N in the topsoil (= uppermost soil horizon) of the Wind River Range and the European Alps.

Fig. 5. Stocks of stable C and N as a function of time.

Fig. 6. Modelled trend (using the exponential decay model) of stable C and N concentrations in the topsoil (uppermost soil horizon). WRR = Wind River Range. The fitting parameters are for stable org C: Wind River Range ($a = 2.2$; $b = 0.15$; $k = 0.00052$), Alps ($a = 5.2$; $b = 0.2$; $k = 0.0035$) and for stable N: Wind River Range ($a = 0.32$; $b = 0.05$; $k = 0.00042$), Alps ($a = 0.7$; $b = 0.05$; $k = 0.002$).

Fig. 7. Relationship between the total organic C stocks (European Alps and Wind River Range) and soil thickness. Soil thickness is also plotted against the factor *Time*.